Incorporating Productivity Improvements Into Cost-Benefit Analyses of Lighting Features in the WELL Building Standard Version 2

Incorporating Productivity Improvements into Cost-Benefit Analyses of Lighting Features in the WELL Building Standard Version 2

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Abstract

Workplace lighting has a significant impact on worker productivity. Lighting can either cost or save a business millions of dollars based on how it impacts worker performance. This thesis analyzes how various lighting conditions impact office workers as part of an effort to develop a more accurate cost/benefit analysis for implementing each of the lighting features of the WELL Building Standard version 2 (WBSv2).

This study was conducted to answer the following research questions:

1. Do each of the lighting features in the WBSv2 have sufficient evidence to warrant inclusion of productivity improvements in a cost/benefit analysis?
2. Which lighting and/or controls improvements in the WBSv2 offer the greatest Return on Investment (ROI) once productivity benefits are included?
3. Are the benefits of upgrading lighting features to meet the WBSv2 worth the cost of implementation?

To answer these questions and to calculate realistic costs and benefits of implementing each feature, an existing office space was selected to serve as a model. This allowed for access to Revit building files, a Bill of Materials for the lighting and controls systems and the ability to measure the actual lighting conditions at each workstation. Analyses were conducted to determine whether or not the model automatically met the requirements of each feature and if not, determine the costs required to achieve them.

The analyses showed that the model office space automatically achieved 10 out of 14 possible points. Additionally, this study predicts that with an investment of $191,442 to upgrade the lighting and controls conditions in the model office space it could lead to worker productivity improvements worth $6,591 per employee per year for a total value of approximately $1,417,080 per year.

Analyses determined that in the model office space six out of the eight lighting features in the WBSv2 are likely to pay for themselves as a result of increased productivity. The feature with the fastest ROI is Feature L01 Light Exposure and Education. Analyses showed that moving an employee from a windowless office space to an office with windows and views can lead to increased productivity worth $5,600 per employee per year. The two features that did not have sufficient evidence pointing toward productivity improvements in the model office space were Features L06 Visual Balance and L07 Electric Light Quality.

Analyses of existing research into how light levels impact productivity led to a significant regression equation showing that worker productivity improves 0.065% for each foot-candle increase in light between 5 and 371 foot-candles. Productivity increases of over 10% are possible by increasing illumination levels from 50 to 200 foot-candles. The most practical means to achieve light levels of 200 or more foot-candles is to design buildings in a manner that maximizes the availability of natural light while minimizing solar glare and seating as many workers as possible near windows. This would contribute toward five of the eight lighting features of the WBSv2 while enabling a business owner to benefit from the majority of lighting related workforce productivity increases.

Dedication

This thesis is dedicated to my parents. To my amazing mother, Teri Headrick, who lovingly inspires me to realize my potential. To the memory of my father, David Taylor, who taught me to enjoy life, appreciate nature and to try to leave every place I visit better than I found it.

Acknowledgements

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I would also like to thank my Research Advisor, Associate Director Dr. Mark Leighton at Harvard Extension School. Mark's excellent guidance enabled me to develop this thesis over the course of numerous revisions and I am very pleased with the result.

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Finally, I want to thank Adam Hemphill for his support and encouragement throughout my graduate studies, including the yearlong process of researching and writing this thesis.

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Definition of Terms

Annual Sun Exposure (ASE): the portion of a building that receives too much direct sunlight, which can lead to visual discomfort (glare) or increase cooling loads. Specifically, ASE measures the percentage of floor area that receives at least 1000 lux for at least 250 occupied hours per year.

Correlated Color Temperature (CCT): the color of white light expressed as a measurement in degrees Kelvin. “Warm” white light is approximately 2,700 degrees Kelvin while “cool” white light is approximately 5,000 degrees Kelvin.

Equivalent Melanopic Lux (EML): a metric derived using factors for each wavelength of light exposure and is weighted toward the ipRGCs rather than the cones. It is calculated by multiplying the measured lux by a ratio of how biologically active the light source is.

Indoor Environmental Quality (IEQ): encompasses building environmental conditions that impact the health and well-being of building occupants.

Intrinsically Photosensitive Retinal Ganglion Cells (ipRGCs): a type of retinal neuron that expresses the hormone melanopsin, which helps synchronize mammalian circadian rhythms.

Model Office Space (MOS): building used as a model for the cost-benefit analysis.

Spatial Daylight Autonomy (sDA): area of a space that receives sufficient daylight. Specifically, the % of floor area that receives at least 300 lux for at least 50% of the annual occupied hours.

Suprachiasmatic Nucleus (SCN): a nucleus in the hypothalamus of the brain responsible for the regulation of physiological circadian rhythms. There are two SCNs in the hypothalamus.

Visible Light Transmittance (VLT): amount of light in the visible portion of the spectrum that passes through a glazing material. A higher VLT means there is more daylight in a space.

WELL Building Standard (WBS): performance-based building standard that measures, certifies and monitors various aspects of the built environment that impact health and wellbeing.

Chapter I

Introduction

Studies of the visual and biological effects of light show that lighting conditions in commercial office buildings have a substantial impact on building occupants both within and outside of the workplace (Askaripoor et al., 2018). Poor office lighting conditions negatively impact employee health, cognitive performance, productivity, absenteeism, and a number of other ancillary factors that negatively impact a business's profits (Bommel & Beld, 2004). Lighting improvements and biologically appropriate lighting design may lead to benefits that reduce personnel costs, which are a business' greatest operating expense (World Green Building Council, 2014).

The WELL Building Standard (WBS) is an above-code building standard that encourages building owners and designers to incorporate evidence based design to promote the health and well-being of building occupants (Delos, 2016). Lighting is an important component of the WBS. The WBS either requires or gives credit to specific lighting conditions that are suspected or known to have wellness related benefits. Implementing these lighting features sometimes requires a substantial investment. When building professionals consider implementing these features it can be difficult to estimate the costs and benefits (Clements-Croome, 2006). This may lead to the selection of the lowest cost or easiest to achieve features rather than features that might offer the greatest benefits to workers.

Health and well-being are subjective and difficult to isolate and quantify. As a result of the difficulties in measuring health and wellness benefits they are often disregarded when making design decisions. If scientific evidence and research related to the benefits of improved lighting conditions were compiled and the values of those benefits were aggregated to help determine realistic estimates, that information could be a valuable tool for building and design professionals.

There is ample evidence showing that when workers move from a traditional building into a “green” building or a building with improved indoor environmental quality (IEQ) their productivity often improves significantly (Kats, 2003). WELL Certified buildings are a type of “green” building with considerably more emphasis on improving the health and well-being of building occupants (Delos, 2016). As a result, workers in WBS certified buildings may exhibit even greater improvements in productivity than they would in a typical “green” building. Post-occupancy research shows that in some cases productivity improvements in WBS certified buildings can be nearly double the productivity benefits of typical LEED Certified buildings (Chung, 2017; Kats, 2003).

Research Significance and Objectives

This thesis explored whether lighting features in the WELL Building Standard version 2 (WBSv2) are likely to lead to financial benefits through reduced operating costs and increased productivity. If there is scientific evidence that a lighting feature is likely beneficial, I estimated a value of those benefits. A building model was created to help estimate the costs as well as the value of some of the most significant benefits for each of the lighting features in the WBSv2. Comparing these costs and benefits can help designers and building owners make more informed decisions about incorporating specific lighting related improvements into a building's design.

Background

A good lighting and controls design can positively impact all three pillars of sustainability (People, Planet and Profits) by improving the health and well-being of building occupants, decreasing energy consumption and reducing business operating expenses (World Green Building Council, 2014). Building owners, developers and designers are often familiar with the costs of lighting and controls but few are familiar with the non-visual effects of light on building occupants (Abdou, 1997). Most building professionals would be unable to readily approximate the value of the intangible benefits of good lighting conditions (Abdou, 1997).

There are currently no comprehensive research reviews that quantify ancillary benefits of the features in the WBSv2. There are also no published studies on the costs of implementing the WBSv2 lighting features. There are however, hundreds of studies on the impact of individual lighting conditions and how they affect building occupants. Most of these studies report correlations or research significance and do not attempt to quantify or monetize results. Efforts to estimate a value for these ancillary benefits are important because they can have a substantial impact on a business's operating costs.

Business Case for Focusing on Employee Health and Wellness

Research shows the potential for financial benefits by improving indoor environments is far greater than the costs of such improvements in office buildings (AT Kearney, 2015; Leyten & Boestra, 2003; Fisk & Rosenfeld, 1997; Romm & Browning, 1998). Employee productivity improvements due to improved IEQ are often significantly greater than the "hard" or tangible benefits that are typically considered in ROI calculations and cost-benefit analyses (AT Kearney, 2015).

In 2016 the real estate investment management company Jones Lang LaSalle trademarked the 3-30-300 Rule™, a rule of thumb that shows the typical distribution of a business's annual operating expenses (Justia, 2016). The rule illustrates that when analyzing a building, on average, approximately $3 per square foot per year is spent on utilities, $30 per square foot per year on rent, and $300 per square foot per year on payroll. Roughly 10% of a business's annual operating expenses are spent on people. Focusing on productivity improvements of the workforce could lead to some of the greatest revenue savings in a commercial building (Jones Lang LaSalle, 2016).

A number of studies of office buildings have highlighted the disproportionately high costs of workers. Personnel costs are estimated to be 112 times greater than energy costs in the workplace (Browning, et al., 2012). For every dollar spent on construction, five dollars were spent on building operating costs and 200 dollars were spent on staffing and business operating expenses (Evans, Haryott, Haste, & Jones, 1998). Building costs accounted for 2%, operating and maintenance costs were 6% and personnel costs account for 92% (Osso, Walsh, & Simon, 1996). Workers' salaries and benefits make up more than 75% of the cost of doing business while all utilities combined total less than 2% on average (BOMA, 2000).

The WELL Building Standard (WBS)

The WBS is the first building standard primarily focused on human health and wellness and it was created by combining medical and scientific research with behavioral science and environmental health research (WELL Certified, 2018b). The WBS was originally released in October of 2014 and later updated to the WBS version 2 (WBSv2) Pilot in May of 2018 (International WELL Building Institute, 2019b). The WBSv2 is expected to go into effect in 2020 (WELL Certified, 2019).

The WBSv2 is comprised of ten wellness concept categories, one of which is lighting. Each of the WELL concepts are comprised of multiple features that are either mandatory preconditions or optional optimizations (Delos, 2016). The lighting concept of WBSv2 has two mandatory preconditions and six optional optimizations (Table 1).

In order to achieve a WBS certification, a building must meet all preconditions and earn a minimum number of points in order to achieve higher levels of certification (International WELL Building Institute, 2019b). If all of the preconditions are achieved a project can earn WELL Core Bronze with 40 points, Silver with 50 points, Gold with 60 points and Platinum with 80 points (WELL Certified, 2018b).

Table 1. Lighting features in the WBSv2 (Delos, 2016).

Feature Number	Feature Name	Precondition or Optimization?
L01	Light Exposure and Education	Precondition
L02	Visual Lighting Design	Precondition
L03	Circadian Lighting Design	Optimization
L04	Glare Control	Optimization
L05	Enhanced Daylight Access	Optimization
L06	Visual Balance	Optimization
L07	Electric Light Quality	Optimization
L08	Occupant Control of Environments	Optimization

Financial Impact of Lighting

Research pertaining to how light affects building occupants seldom allows for a direct calculation of the value of such benefits (Clements-Croome, 2006). Studies of how lighting conditions impact building occupants often provide qualitative results that are difficult to assign a monetary value. Examples of the ancillary benefits that are difficult to quantify include increased cognitive function, decreased stress, improved alertness, better sleep and reduced error rates. When combined, the cumulative impact of these benefits can lead to productivity improvements of several percent, leading to considerable economic impacts for employers. MacNaughton et al. (2015) estimated that, for an average U.S. office worker, a 1% performance improvement is worth $812.50 per employee per year. For a 207,740 square foot office building, which is the average size of a WELL Certified Building (International WELL Building Institute, 2019a) with an average U.S. employee density of 151 square feet per employee (Mehigan, 2016), each

1% improvement in employee productivity across could provide a value of roughly $1,100,000.00 per year to an employer.

The right quality, quantity and delivery of light can not only increase productivity (Juslen, Wouters, & Tenner, 2007), it can improve health and well-being (Bommel, 2006), and work quality and performance (Bommel & Beld, 2004). Lighting impacts visual and verbal-intellectual performance, mood, rate of errors, physical and mental fatigue and a number of other conditions that affect worker performance and productivity (Veitch & Newsham, 1998).

Worker Productivity

The workplace is one of many factors known to influence employee productivity. Productivity is influenced by both the individual and the system in which they work (Figure 1) (Boyce et al., 2003). The indoor environment impacts worker well-being, performance, motivation, job satisfaction and technical competence, all of which have a strong influence on worker productivity (Boyce et al., 2003). Indoor environmental quality (IEQ) is affected by a variety of environmental factors such as lighting, temperature, indoor air quality, acoustics, etc. These environmental factors affect health positively or negatively, which can further influence worker productivity.

Many "green" buildings have IEQ attributes that lead to improved health and increased worker productivity (Singh, Syal, Grady, & Korkmaz, 2010). One of the goals of the WBSv2 is to further optimize the indoor environmental factors beyond traditional "green" buildings in order to minimize negative health factors (Delos, 2016). In office buildings, HVAC and lighting systems (including windows) are thought to be the

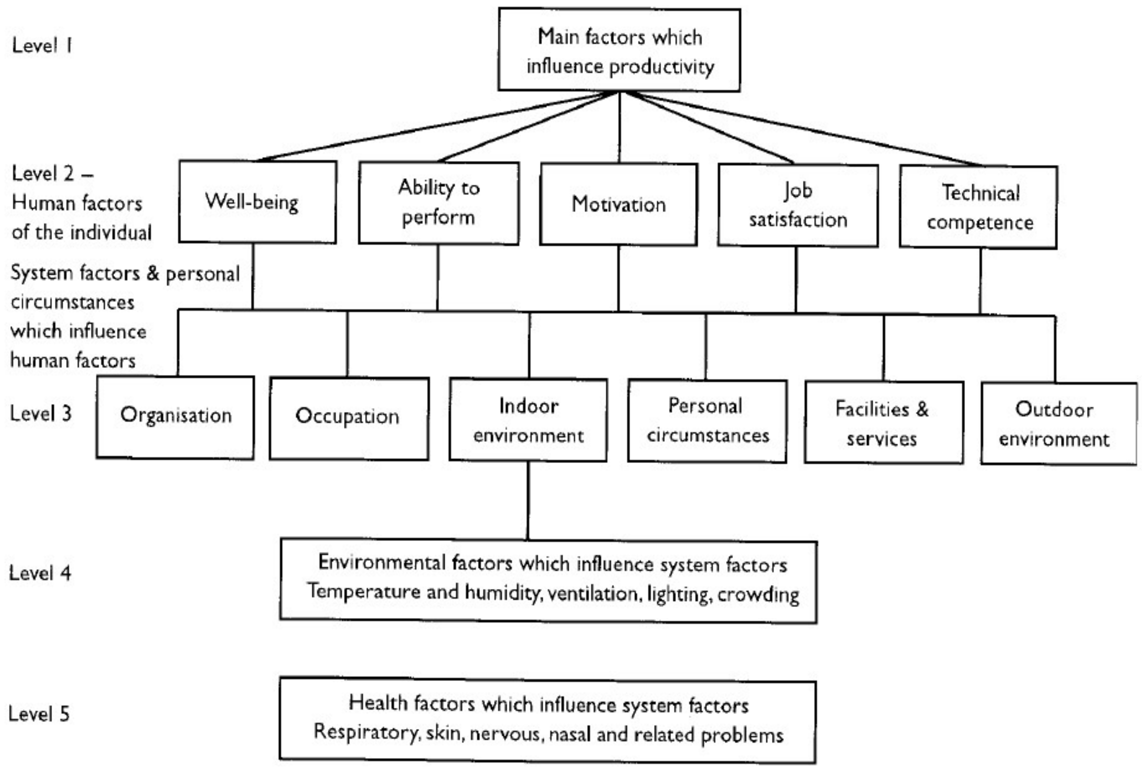


Figure 1. Main factors known to influence productivity (Boyce et al., 2003).

building systems most likely able to contribute to improved worker performance and productivity in office buildings (Fisk & Rosenfeld, 1997).

There is evidence that in many cases, when workers move from a traditional building into a WELL Certified building they become more productive. In a small study of four WELL Certified buildings in California, 75% of employees surveyed self-reported an increase in productivity, with 20% of respondents reporting a significant increase (Richardson, 2018). Some benefits of the WBSv2 may be immediately apparent once an employee begins working in a WBSv2 certified space, but some of the health, well-being and performance benefits may become more apparent over time (Boyce et al., 2003).

Perhaps the most effective way to measure the full impact of a WELL Certified Building is to conduct a field study with employees who have moved from a traditional code compliant space, into a new WELL Certified space. For example, the staff of The American Society of Interior Designers (ASID) National Headquarters moved from a traditional code compliant building into the world's first LEED Platinum and WELL Platinum certified office space. Conditions prior to the move and again one-year post occupancy were measured. In the new WELL Platinum Certified space, collaborative work increased by 9%, physical and mental health scores improved, absenteeism decreased by 19% and worker performance increased by 16% (Chung, 2017). The new WELL Platinum Certified space yielded an estimated increase of $694,000 financial impact to ASID's bottom line during the first year of occupancy and a $7,000,000 increase in financial impact is expected over a ten year period for the 8,500 square foot office space (Chung, 2017).

Impact of Lighting on Worker Productivity

Lighting is one of the most important environmental factors that influence worker performance (von Herrmann, 1989). It is also likely the least expensive IEQ component that can significantly improve human performance but many building professionals aren't aware of this fact (Abdou, 1997). The relationship between lighting and worker productivity has been studied since the 1920s (Halonen, Tetri, & Bhusal, 2010) and among researchers it is well known that a poor luminous environment can result in a deterioration in worker performance and productivity (Parsons, 2000). Lighting can affect human performance through the visual, circadian and perceptual systems via a number of different mechanisms (Boyce et al., 2003). These mechanisms include visual performance, visual comfort, visual ambience, interpersonal relationships, biological clock, stimulation, job satisfaction, problem solving, the halo effect, and the change process (Juslén & Tenner, 2005).

Figure 2 displays a conceptual framework of the routes by which lighting can impact human performance. The lighting features in the WBSv2 were designed to improve the positive impact lighting can have on many of these routes, including light spectrum, retinal illuminance, time of day lighting, circadian lighting, visual comfort, glare, flicker, luminance contrast, color difference and more.

This framework shows that the impact lighting has on performance can be rather circuitous. Something as unique and personal such as a worker's culture and experience can influence their expectations of their indoor environment (Boyce et al., 2003). If these expectations are met or exceeded they can have a positive impact on the worker's mood, which could lead toward increased motivation, improved performance and increased productivity. If the worker's expectations are not met, the opposite may occur (Boyce et al., 2003). The routes by which lighting influences worker productivity makes it difficult to precisely quantify the performance and productivity effects of altering the luminous environment.

Much of the variability in research results measuring the impact of the parameters of the luminous environment may be due to the inability to account for human factors (Gligor, 2004). Even well designed studies can have results skewed by a subject's personal preferences, history, culture, social interaction, motivation and health (Gligor, 2004).

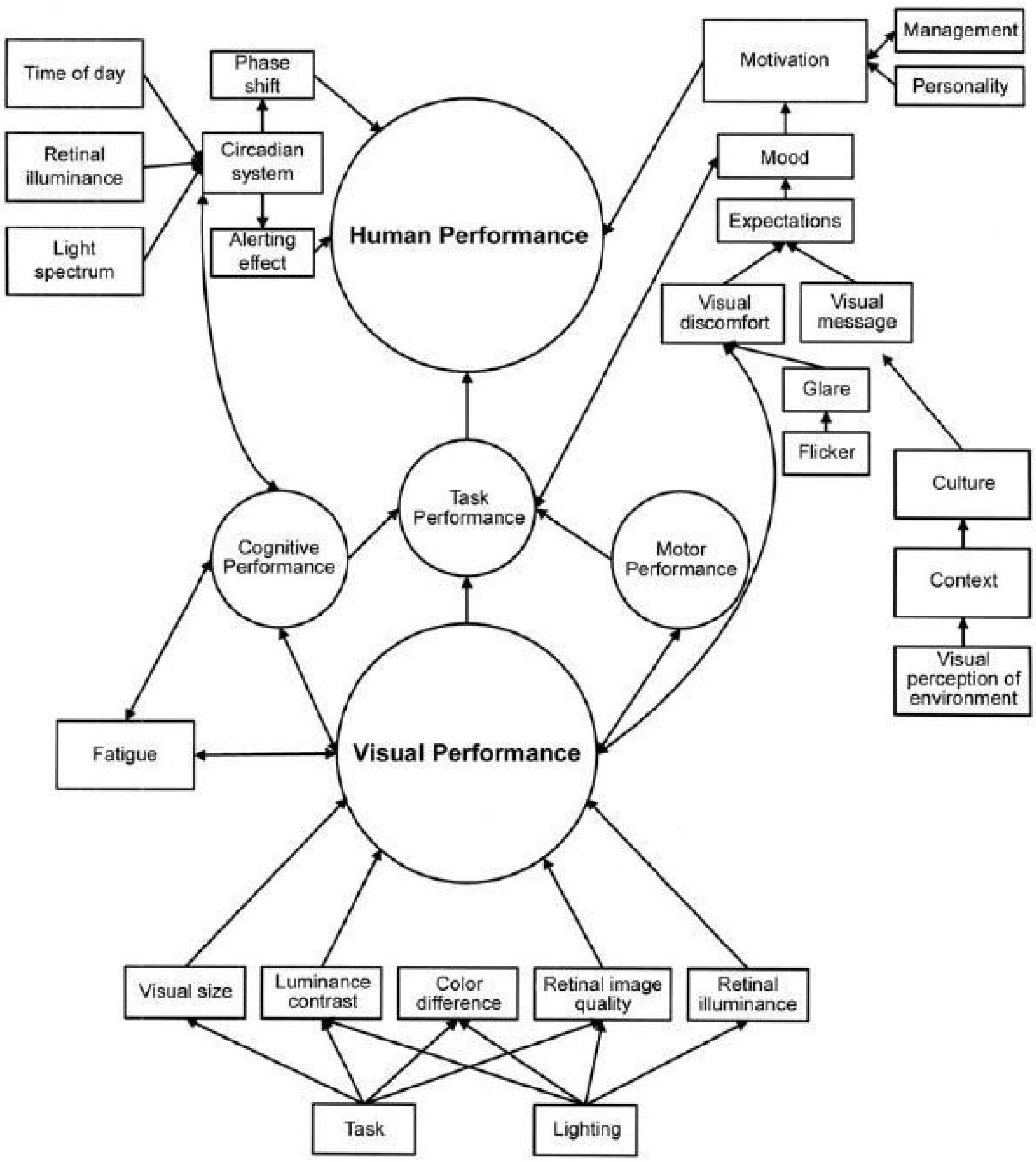


Figure 2. Routes by which lighting can influence human performance (Boyce et al., 2003).

More than 20 parameters of the luminous environment can act through a chain of mechanisms on human physiological and psychological factors, which influence human performance and productivity (Figure 3). The WBSv2 lighting features address each of these lighting parameters to some extent (Delos, 2016).

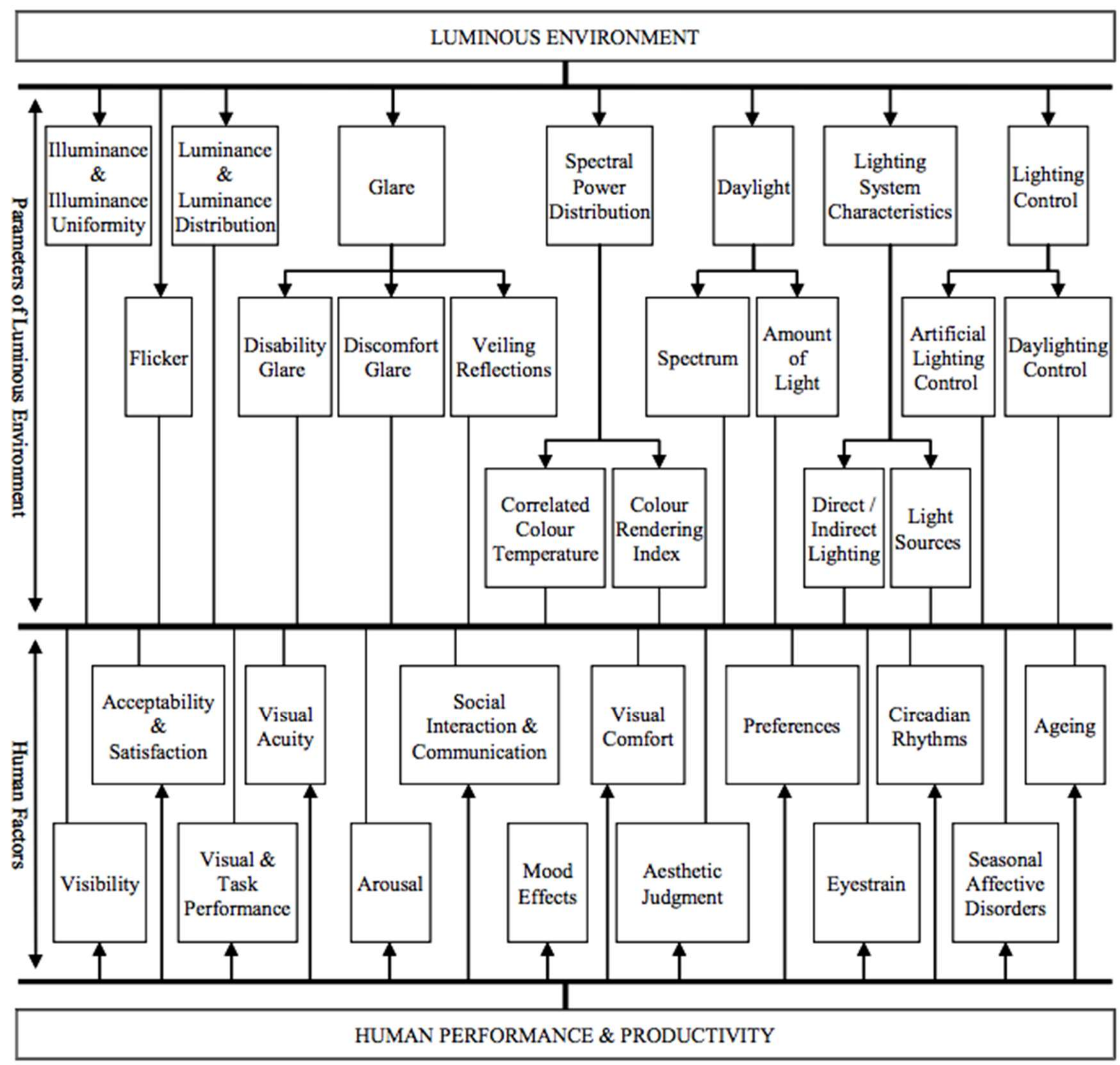


Figure 3. The impact of the luminous environment on human performance and productivity (Gligor, 2004).

In order to test different lighting parameters while minimizing the impact of sleep, diet, health, etc. researchers may test a variety of different luminous conditions back-to-back which can lead to increased fatigue and diminished performance on tests of cognitive function, performance and productivity. Additionally, worker performance may be limited by the weakest link in IEQ. If the lab is hot or cold, if the indoor air quality is poor with high CO2 or high VOC levels, if the testing location is noisy, any of these conditions may dampen the positive effects of improving specific lighting parameters (MacNaughton et al., 2015).

Research into the impact of light on human performance has changed considerably in the past 20 years since the discovery of ipRGCs and the impact of spectral power distribution on the circadian system (Figueiro, Nagare, & Price, 2018). There are several additional light information pathways from the eye to the brain that are still not fully understood (Figure 4) (Veitch, 2005).

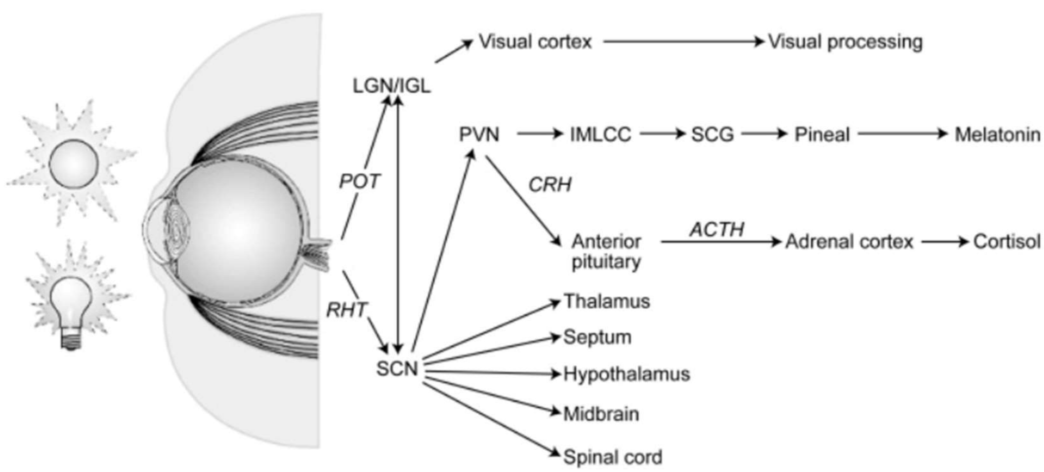


Figure 4. Diagram of the eye-brain pathways showing how light is converted into neural signals via the optic nerve (Veitch, 2005).

In 2002 researchers learned that ipRGCs signal the suprachiasmatic nucleus (SCN) to regulate the release of melatonin and this led to significant changes in lighting design and recommended lighting exposure (Veitch, 2005). It is likely that as other pathways illustrated in Figure 4 become better understood there may be additional changes to lighting best practices that may further impact health and well-being of building occupants (Veitch, 2005). As more is learned about the biological effects of light, researchers will become better equipped to test specific luminous conditions to discover the true impact on human health and performance.

Benefits Addressed by Features of the WBSv2

The lighting features of the WBSv2 were created to allow building occupants to realize the various benefits outlined in the following sections.

Benefits Related to Windows and Views

Workers with windows in their workplace score higher on quality of life measures and have better outcomes in measures of sleep quality, sleep efficiency, sleep disturbances and daytime dysfunction (Boubekri, Cheung, Reid, Wang, & Zee, 2014). Workers with windows slept an average of 46 minutes more per night during the workweek compared to workers without windows (Boubekri et al., 2014). Insufficient sleep and poor sleep quality are associated with reduced health, increased fatigue, deterioration of performance, decreased cognitive function and an increased rate of accidents and injuries (Boubekri et al., 2014).

Office workers with windows in their offices spend approximately 15% longer on work tasks than comparable workers in interior offices, with an estimated benefit of $10,000 per occupant per year (Figueiro, Rea, Rea, & Stevens, 2002).

Windows allow building occupants to have access to views to the outside. Views provide meaningful mental stimulation and biophilia, the belief that there is an innate emotional affiliation of human beings to other things, both plant and animal (Kellert & Wilson, 1993). According to the California Energy Commission (2003), office workers with the best views to the outside were more productive and they performed up to 25% higher on tests of mental function than peers who had no views. Call center workers with the best views processed calls 6% to 12% faster compared to workers with no view. Office workers with the best views reported better health and less fatigue compared to workers without views (California Energy Commission, 2003). A study by Carnegie Mellon reported that workers with the best views report fewer health problems (Edwards, Torcellini, & Laboratory, 2002). Employees experiencing fewer health problems are likely to use less sick leave. Elzeyadi reported that having a view in an office reduced sick leave days by approximately 6.25% (Elzeyadi, 2011). Workers with the best views used approximately 57 hours of sick leave, while someone with no view used approximately 68 hours (Elzeyadi, 2011).

Benefits of Daylight

Natural daylight is an essential component of a building's lighting design. Properly controlled daylight increases worker performance (Elzeyadi, 2011), improves health, reduces absenteeism, and increases productivity (Franta & Anstead, 1994). High levels of daylight improve memory and attention span (California Energy Commission, 2003), significantly improve auditory reaction time (Rahman et al., 2014), reduce depression and improve sleep quality (Figueiro et al., 2017). Measures of cognitive function improve up to 20% above average for office workers seated in areas with daylight and/or views. For workers without access to daylight and/or views cognitive test scores drop as low as 24% below average (Edwards et al., 2002).

Although daylight has been shown to have a positive impact on worker performance, it is important to minimize solar glare, which can reduce employee productivity by as much as 21% (California Energy Commission, 2003).

Benefits of Circadian Lighting

Throughout human evolution daylight has been the primary source of light and humans have adapted to its properties. Technically daylight is just another source of electromagnetic radiation with wavelengths that are visible to humans, and electric lighting systems can be designed to mimic many of the sun's lighting parameters (Boyce et al., 2003). However, daylight has a greater probability of maximizing visual performance than most forms of electric lighting because it tends to be delivered in large amounts with a spectrum that ensures excellent color rendering (Boyce et al., 2003).

Daylight contains properties that encourage human circadian entrainment including the proper intensity and spectral power distribution at the appropriate times throughout the day (Figueiro et al., 2018). Both daylight and electric light impact human circadian rhythms, the 24-hour light/dark and sleep/wake pattern. Disruption of this pattern can lead to poor sleep, decreased performance, inadequate hormone production, diabetes, obesity and diseases such as cancer (Figueiro et al., 2018).

One of the ways light influences human circadian rhythms is by stimulating retinal cells called intrinsically photosensitive retinal ganglion cells (ipRGCs), which convert light into electrical signals that are sent to the suprachiasmatic nuclei (SCN) which sets the body's circadian rhythm (Figueiro et al., 2018). When light stimulates ipRGCs it can lead to a suppression of the production of the hormone melatonin (Linhart, 2010). Melatonin induces sleep while its suppression leads to wakefulness (Skocbat, Haimov, & Lavie, 1998). The ipRGCs are most sensitive to blue light with wavelengths around 460 nanometers (Figueiro et al., 2018).

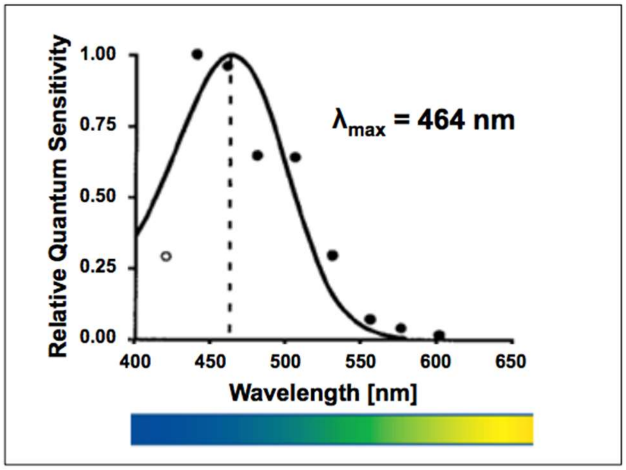


Figure 5. C(λ)-curve. Action spectrum for melatonin suppression in humans, showing a peak at 464 nanometers (Linhart, 2010).

Different wavelengths of light impact the production of melatonin (Figure 5). Exposure to blue light significantly improves auditory reaction time because blue light activates the cognitive neural centers of the brain (Rahman et al., 2014).

Both daylight and electric light can elicit an acute, alerting effect on humans, similar to the effects of caffeine consumption, at any time of day or night (Figueiro et al., 2018). High light levels during the day aligns circadian rhythms to a day-active and night-sleeping pattern and increases alertness during working hours (Figueiro et al., 2018). Office workers receiving high levels or circadian effective light in the morning fall asleep faster, sleep better, and report less stress and better moods (Figueiro et al., 2018).

For circadian entrainment it is important to control lighting over a 24-hour cycle. Proper lighting in the workplace can be beneficial but if a worker is exposed to improper lighting at home it negates the effects of workplace lighting (Boyce et al., 2003). By educating workers about circadian lighting it can enable them to make decisions about the light sources they use at home including the intensity and spectral power distribution, which could help positively impact their circadian entrainment.

Benefits of Lighting for Visual Acuity

The illuminance recommendations required by the WBSv2 are predominantly based on visual performance (WELL Certified, 2018b). Light levels impact visual performance, which in turn influences task performance, which finally influences overall individual worker performance (Juslén & Tenner, 2005). Low light levels can lead to sore eyes, blurred vision, headaches (Boyce et al., 2003) and an increase in mental fatigue, all of which are known to impair worker performance (Carli, Giuli, & Zecchin, 2008). In addition to improving visual performance, light levels impact worker's moods which affects individual performance (Juslén & Tenner, 2005.) Higher light levels also increase alertness and decrease sleepiness which leads to improved worker performance and higher productivity (Clements-Croome, 2006; Juslén & Tenner, 2005).

Some researchers believe that once there is enough light to see task details, additional light may not improve performance. For instance, Gifford et al. reported that contrasts between 70 lx and 486 lx illuminance levels did not affect task performance but contrasts between 70 lux and 1962 lx had a statistical effect but that effect diminished after a short adaptation period (Clements-Croome, 2006). However, most research relating to lighting and productivity suggest that increasing illuminance leads toward increased worker productivity (Abdou, 1997). Abdou reported that there are no studies that show increased illuminance decreases output and there are very few studies that suggest that decreased illuminance increases output (Abdou, 1997).

Juslén and Tenner (2005) examined all known studies relating to lighting change effects on worker output, concluding there is an effect of the illuminance level on performance across these studies Figure 6). The steepest curves showing increased productivity occurred when a study started with very low illuminances. Once the illuminance is sufficient for visual performance the rate of increase in worker productivity slows down (Juslén & Tenner, 2005).

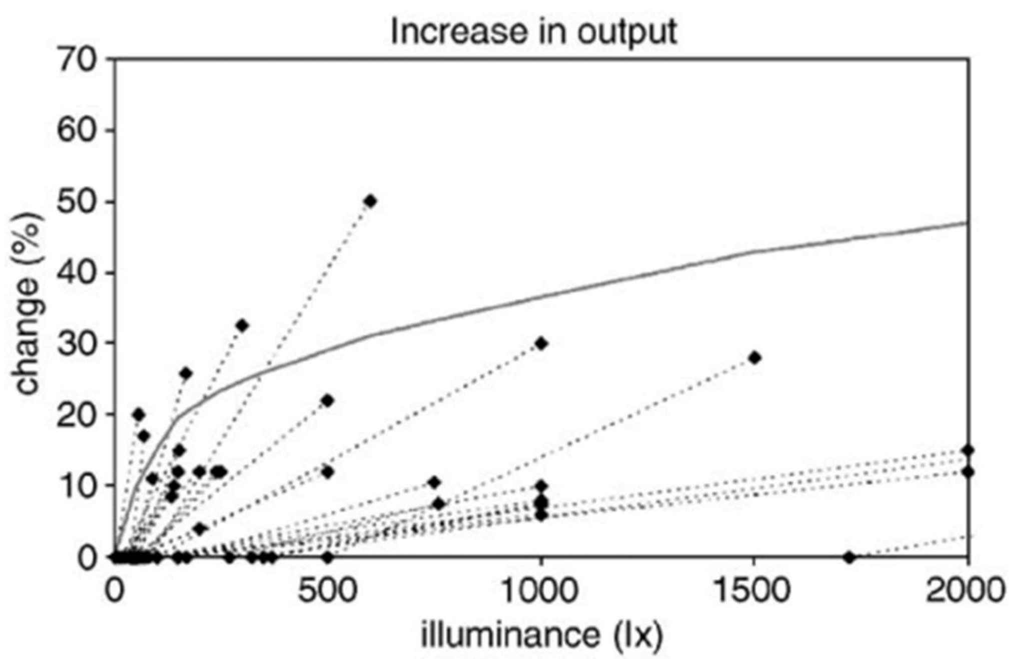


Figure 6. Lighting change effect for work output results of 29 studies (Juslén & Tenner, 2005).

Smolders, deKort and Cluitmans (2012) found that higher illuminance induces alertness during office hours. Workers were exposed to two light levels, 200 lux and 1000 lux and the results show that higher illuminance can improve feelings of alertness and vitality, as well as objective performance and physiological arousal.

Higher illuminance in the workplace can lead to better sleep at night. Workers in green certified buildings had 6.4% higher sleep scores than those in high performing non-green-certified buildings. A 6.4% higher sleep score correlates to a 0.72% increase in cognitive function (MacNaughton et al., 2017). The higher sleep scores were attributed to the fact that on average, the certified green buildings were 19.6 foot-candles brighter than non-green certified buildings (MacNaughton et al., 2017).

Benefits of Age Specific Lighting

As humans age their lenses slowly become less transparent (Kessel, Lundeman, Herbst, Andersen, & Larsen, 2010). This prevents some of the light from entering the retina. Increasing age is associated with gradually decreasing light transmittance at all visible wavelengths with shorter wavelengths being affected most prominently (Kessel et al., 2010). By age 60 only 20% of blue light is transmitted to the retina (Dillon, Zheng, Merriam, & Gaillard, 2004). This can have a significant impact on circadian rhythms, sleep, performance, productivity, visual acuity and safety. Aging lenses impact the transmittance of different wavelengths of light (Figure 7). Additionally, on average, due to age related lens changes, a person in their sixties would require 2.15 times more light to have the same visual acuity as a teenager (Figure 7) (Illuminating Engineering Society, 2011) .

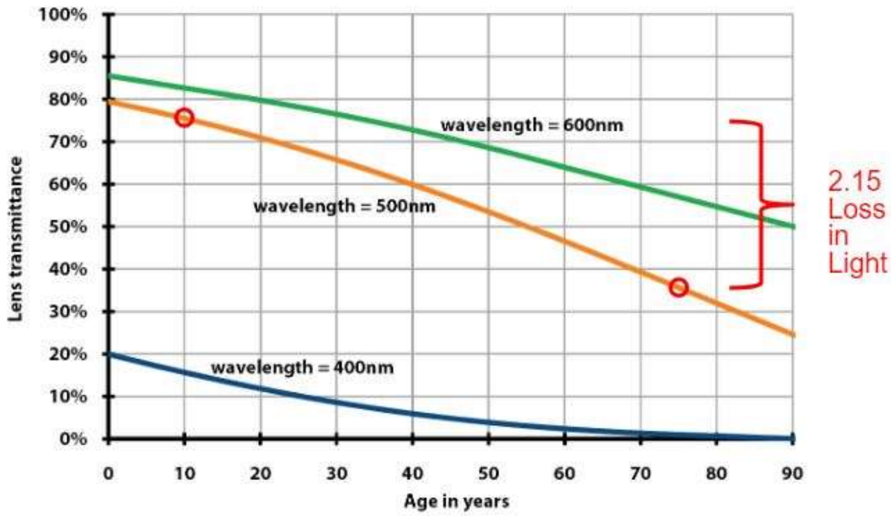


Figure 7. Age related lens transmittance loss by wavelength (Illuminating Engineering Society, 2011).

In addition to lens changes, pupil size decreases with age and when combined with the loss in light transmittance approximately five times more light is required to achieve the same visual acuity as a young person (Figure 8). As luminance increases performance increases in older individuals (Boyce, 1973).

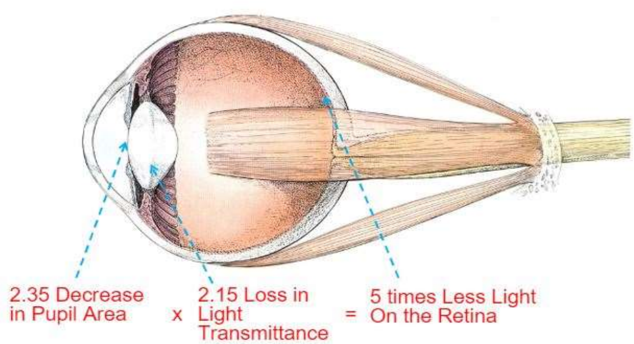


Figure 8. Effects of aging on the human eye (Illuminating Engineering Society, 2011).

Benefits of Visual Comfort

Visual comfort describes how easily a subject can view tasks and it is often described using the negative terms of discomfort glare, disability glare and veiling reflections (Juslén & Tenner, 2005). Each of these conditions can result in visual discomfort, which may lead to lower productivity. Discomfort glare causes pain or annoyance, which affects the ability to concentrate on a task and therefore reduces performance (Juslén & Tenner, 2005). Discomfort glare in an office environment is primarily caused by windows or luminaires. Disability glare (also known as veiling luminance) results from light scattering in the eye leading to decreased contrast and reduced visibility. Examples of disability glare include reflective screens and glossy magazine pages that bounce light, making it difficult to read (Juslén & Tenner, 2005). Veiling reflections are reflections of a large luminance area on a task, resulting in reduced contrast between the task and background.

Benefits of Reducing Solar Glare

Solar glare from windows can reduce worker performance by as much as 21%, which would equate roughly to a 10.5% reduction in productivity (California Energy Commission, 2003). Other researchers have reported that glare reduces productivity by 12.3% (Wymelenberg, 2013).

Solar discomfort glare can be reduced by utilizing solar shades or blinds. It is important that they be actively controlled in order to minimize the negative impacts of glare without also reducing the benefits of daylight and views. Most blinds in office buildings are not actively controlled and in some cases blinds are left closed for days, months or even years (Boyce et al., 2003).

Benefits of Reducing Glare from Electric Light Sources

Evidence suggests that glare from electric light sources can have a significant impact on worker productivity. The Institute of Electrical and Electronics Engineers (IEEE) reported that under high levels of discomfort due to glare there is an associated 3% decrease in visual task efficiency (IEEE, 1992). If only 50% of overall performance is based on visual task efficiency this would suggest discomfort glare can lead to a 1.5% decrease in productivity.

Field studies on the subject show a much greater impact. Abdou (1997) reported results showing that lighting changes designed to reduce glare led to a 13.2% increase in productivity in spite of lowering illuminance from an average of 142 foot-candles to an average of 115 foot-candles. In two field studies where high-glare parabolic louvered fixtures were replaced with lensed indirect lighting, one business reported a 3% increase in productivity and a Reno post-office reported a 6% increase (Loftness et al., 2003).

Visual discomfort and glare can be significantly reduced by increasing general illuminance levels, luminance of room surfaces and luminance distribution (Aaras et al., 1998).

Benefits of Luminance Balance

Excessive luminance ratios may lead to eyestrain, headaches and blurred vision (Boyce et al., 2003.) The ratios that are considered excessive vary by researcher. Veitch and Newsham (2000) reported that luminance ratios on the order of 10:1 are the upper limit for visual comfort. Egan (1983) recommended that ratios be a maximum of 40:1. Osterhaus (2002) recommended maximum luminance ratios of 100:1. However, Osterhaus also reported that office workers could be comfortable and productive under luminance ratios up to 1000:1 if a desirable view of an outdoor environment was available (Osterhaus, 2002).

Some of the luminance ratio requirements in Feature L06 of the WBSv2 are as low as 3:1. Several studies of daylit offices showed that there were luminance ratios far higher than the recommended by the WBSv2, but workers were often still satisfied with the lighting conditions (Linney, 2008). While some studies report that productivity decreases as surface luminances increase (Osterhaus, 2002), other studies suggest that luminance ratios of 10:1 or higher are required to stimulate visual interest which leads to increased worker productivity (Veitch & Newsham, 2000). With studies showing acceptable luminance ratios as low as 3:1 and as high as 1000:1, it brings into question whether the conservative ratios in the WBSv2 are likely to have measurable benefits.

Benefits of High Color Rendition / Full Spectrum Lighting

One important capability of the visual system is the ability to perceive colors that are required in the performance of certain tasks (Abdou, 1997). High CRI lamps and full spectrum lighting that allows for high color rendition are important for tasks that require fine color discrimination such as manufacturing but no quantitative research was found showing they have a significant productivity impact for the majority of office workers (Carli, Giuli, & Zecchin, 2008; Fisk & Rosenfeld, 1997; Hedge, 2016; Veitch, 2001).

There were a number of qualitative benefits reported for high CRI and full spectrum lighting that will be discussed in the results section.

Benefits of Managing Flicker

Flicker is a rapid, repeating, wavering fluctuation in light level. Most people are able to detect flicker slower than 50 hertz but some people notice flicker at up to 100 hertz (Lau, 2014). Many fluorescent lamps flicker at 120 cycles per second, higher than most people are able to see, but the sensory systems of some sensitive individuals can still detect the flicker which can lead to health issues and reduced productivity (Government of Canada, 2018). Frequencies between 3 and 70 Hz can cause seizures in sensitive individuals while moderate flicker frequencies, from about 100 hertz to as high as 500 Hz have been associated with adverse health effects such as headaches, eye strain, and fatigue (Lau, 2014).

Flicker from LED light sources may be more noticeable than fluorescent light sources because LEDs flicker between less than 10% and 100% of their light level whereas fluorescent light sources typically flicker between 35% and back to 100% (Government of Canada, 2018).

Low frequency flicker decreases worker performance by interfering with visual processing, reading, visual performance and computer-based task performance (Veitch & Newsham, 1998). As the frequency goes higher flicker becomes less of a problem. Headaches and eyestrain drop dramatically when fluorescent lights are run on high-frequency electronic ballasts (20,000 Hz or higher) when compared to magnetic ballasts with a much slower rate of flicker (Wilkins et al., 1989). High-frequency LED drivers reduce low frequency flicker, leading to fewer incidences of fatigue and eyestrain improved worker performance (Juslén & Tenner, 2005).

Benefits of Tunable Lighting / Adjustable Correlated Color Temperature (CCT)

Studies show that CCT has a significant effect on mood (Juslen et al., 2007; McCloughan et al., 1999), comfort (Wei et al., 2014), cognitive performance (Knez, 2001), sleep (Figueiro, Nagare, et al., 2018) and a number of other parameters known to impact worker productivity. It is difficult to establish general rules relating to color temperature because individual difference and preferences are very significant (McCloughan et al, 1999). Age and gender both play a role in how CCT impacts mood and cognitive performance. In a study of how different age groups are affected by CCT it was discovered that older adults exhibited a negative mood under a 4,000 degrees Kelvin (K) CCT, whereas younger adults showed a more negative mood under a 3,000 K CCT (Knez, 2001). Knez found that participants performed better overall on tests of cognitive function under a "warm" (3,000 K) than under a "cool" (4,000 K) or artificial "daylight" white lighting (5,500 K) (Knez, 2001). Problem solving scores were nearly 20% higher under 3,000 K CCT than they were under 5,500 K CCT (Figure 9).

Askaripoor conducted a study on whether exposure to 2,564 K light could improve alertness and performance compared with 3,730 K, 7,343 K, and dim light conditions during the daytime (Knez, 2001). All three light conditions led to a significant reduction in fatigue and sleepiness and to an increased heart rate and improved performance compared with dim light (Knez, 2001). These lighting interventions can improve worker performance by reducing fatigue and sleepiness, which are one of the biggest causes of human errors and accidents in the workplace (Knez, 2001).

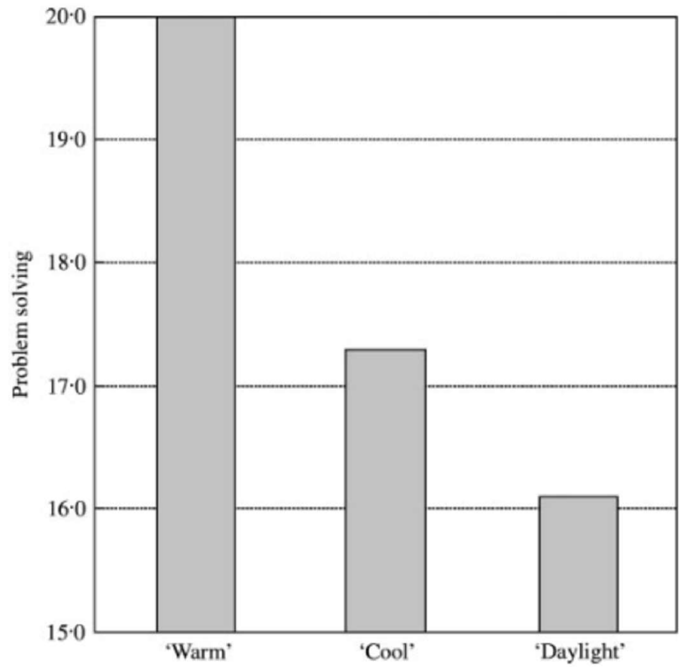


Figure 9. Average problem solving scores under "warm" (3,000 K), "cool" (4000 K) and artificial "daylight" (5,500 K) light sources (Knez, 2001).

The study also found that males and females respond differently to CCT on measures of cognitive function. Men perform worst on tests of long term recall under warm (3,000 K) lighting and best under cool (5,500 K) lighting (Figure 10) while women perform best under warm lighting and worst under cool lighting (Knez, 2001).

People have a stronger response to changes in CCT than they do to changes in light intensity (Wei et al., 2014). Light at 5,000 K is often rated to be too cool and less comfortable compared to 3,500 K (Wei et al., 2014). Surveys indicate that CCT significantly affects the perception of spatial brightness, visual comfort, satisfaction, and self-reported productivity (Wei et al., 2014). Artificial daylight (5,000 K) is often rated to be brighter than 3,500 K but the brightness comes with lower satisfaction, reduced visual comfort, and worse self-reported productivity (Wei et al., 2014).

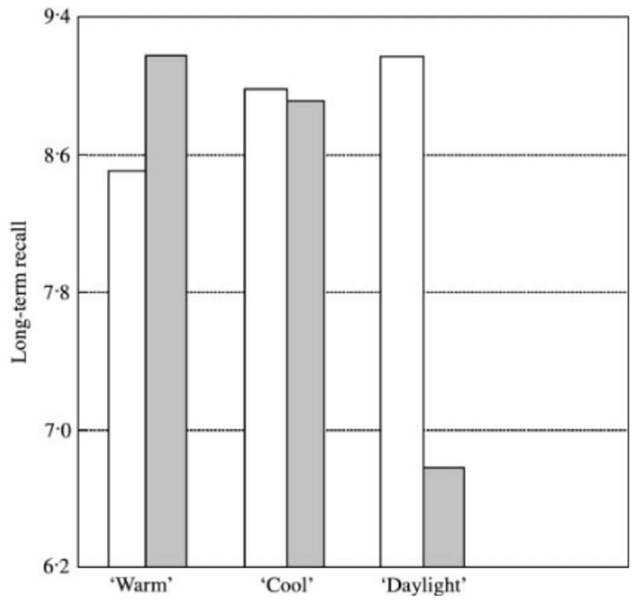


Figure 10. Average long-term recall scores for females and males under "warm" (3,000 K), "cool" (4,000 K), and "artificial daylight" (5,500 K) lighting (Knez, 2001).

Benefits of Personal Lighting Controls

The more the interior climate is centrally controlled, the greater the chance of dissatisfaction and complaints (Bergs, 2002). It is not possible to choose a single illumination level, correlated color temperature (CCT) or window shade position that optimizes the health, satisfaction, and performance of all building occupants at all times (Veitch & Newsham, 2000). Personality, gender, genetics, experience and other factors affect each person's preferred ambience (Juslén & Tenner, 2005). These differences vary from person to person but they also vary within an individual because each person may have different preferences at different times (Juslén & Tenner, 2005). There is a ‘forgiveness factor’ that operates if people feel they can control their environment (Leaman & Bordass, 1999). Personal lighting controls are important because they allow occupants to select a light level that works best for them (Knez, 2001). Personal lighting controls allow building occupants to work under their preferred lighting conditions at all times. Giving workers the ability to select their shade position, preferred lighting level, CCT and/or color can help ensure that office lighting is more suited toward the immediate needs of the building occupants compared to preset levels and studies show that workers prefer these controls (Juslén & Tenner, 2005).

There is a strong correlation between workspace satisfaction and productivity (Bergs, 2002). Positive affect theory states that when workers are happy with their environmental conditions it leads to improved performance, higher productivity and greater effort (Baron, Rea, & Daniels, 1992). Workers with personal controls are more satisfied and more productive (Barnes, 1981; Simpson, 1990). Newsom and Veitch discovered that the further fixed lighting was from a worker’s preferred level the more negative that person’s mood was throughout the day (Veitch & Newsham, 2000). Another study showed that when the lighting was considered too dark a subject’s mood was at its worst, but it improved and reached its highest level when the lighting was considered ideal but when it became too bright the mood declined again (Küller, Ballal, Laike, Mikellides, & Tonello, 2006).

Most scientific literature on the topic of personal lighting controls shows that controls are beneficial, but one study showed personal controls can lead to negative outcomes if a worker is afraid of making the wrong lighting choice (Clements-Croome, 2006). There is evidence that the more building occupants understand how to use lighting controls, the more likely the controls will achieve beneficial results (Clements-Croome, 2006). Providing background information about the luminous conditions lighting controls create and how they work is an important consideration for maximizing the benefits of personal lighting controls (Clements-Croome, 2006).

Benefits of Light Color

The color of light can have several impacts on building occupants. Blue light can affect the body's production of melatonin leading to circadian entrainment as discussed previously (Figueiro et al., 2018). Having the ability to change the color of workspace lighting can take advantage of the benefits of different colored lighting while minimizing the negative effects at different points in the day. Blue light in the morning is beneficial as it has an alerting effect similar to drinking a cup of coffee (Figueiro et al., 2018). The same color of light shortly before bedtime can have the unwanted effect of increasing alertness making it difficult to fall asleep (Figueiro et al., 2018).

Recent studies of the effects of red light show that it has different effects at different times of the day. Sahin et al. (2014) reported that red light improves subjects' response time whereas white light does not (Sahin, Wood, Plitnick, & Figueiro, 2014). The same study showed that high intensity red light increases alertness and performance in the middle of the afternoon, but not in the morning and middle of the day. The study's authors suggest that red light can be used to counter the sleepiness that often occurs after lunch (Sahin et al., 2014).

Another recent study showed that red light with a peak around 630 nanometers can increase objective and subjective measures of alertness at night and during the day

(Figueiro, Nagare, et al., 2018). Several other studies using light that was filtered to remove short-wavelength content show that acute melatonin suppression is not needed to maintain subjective alertness (Figueiro, Nagare, et al., 2018).

To summarize, there is ample scientific evidence that a number of lighting features are beneficial, but which are of greatest value when compared to costs of implementation?

Research Questions, Hypotheses and Specific Aims

Research for this thesis focused on the following questions and hypotheses:

1. Do the lighting features in the WBSv2 (WELL Building Standard version 2) have enough compelling scientific research to warrant productivity improvements being included in a cost/benefit analysis?

   Hypothesis 1: Most of the lighting provisions in the WBS have strong scientific backing but some provisions may be based on limited or controversial scientific research.

2. Which lighting and/or controls improvements offer the greatest ROI once productivity benefits are included?

   Hypothesis 2: Lighting upgrades that enable the indoor environment to more closely mimic nature are likely to have the greatest ROI.

3. Are the benefits of upgrading lighting features to meet the WBSv2 worth the cost of implementation?

   Hypothesis 3: Most features in the WBSv2 have benefits that outweigh the costs once worker productivity is taken into consideration.

Specific Aims

Addressing these questions and hypotheses required completing the following steps:

- Analyze lighting conditions in an existing code-compliant office space
- Develop a list of lighting and lighting control upgrades that will be required in order to meet the WBSv2 lighting features
- Determine the costs of each lighting and/or lighting control upgrade required to achieve each feature
- Research the benefits of these lighting upgrades and determine the value of these improvements in order to develop a more accurate cost/benefit analysis
- Develop a cost-benefit model to compare a baseline office against WBSv2 lighting requirements
- Conduct an analysis to evaluate data and determine which upgrades have the greatest ROI.

Chapter II

Methods

In order to estimate the benefits of each lighting feature in the WBSv2, I analyzed existing literature to segment and quantify potential productivity impacts starting with a high-level overview, then led into a more granular analysis as follows:

1. What do researchers predict the impact the workplace has on employee productivity?
2. For office workers who moved from a standard, code compliant building to an above code "green" building or a WELL Certified Building was there an impact on productivity?
3. What percentage of the overall performance impact can be attributed specifically to lighting related factors?
4. How much of an impact can be attributed to each of the lighting features of the WBSv2?

Due to the complex chain of mechanisms on human physiological and psychological factors as well as study design, potential lurking variables such as poor IEQ and the complex biological processes that are as of yet still unknown, I attempted to uncover general trends in human responses to luminous conditions rather than precise percentages. In order to quantify the value of lighting improvements several assumptions and conversions were necessary. Prior to attempting to calculate the benefits of individual lighting improvements a literature review was conducted to determine the scientific consensus on how much lighting can improve worker performance.

Literature Search

The investigation into productivity related benefits of lighting began with a literature search of research papers, conference papers, books, industry literature, and journal articles. Relevant research was identified through computer-based literature searches and discussions with lighting professionals and researchers. To be included in analysis of quantitative benefits, a study needed to provide benefits in the form of a percentage or a value that could easily be converted into productivity or dollars. If a study reported non-quantifiable results such as "a significant effect", "slight improvement", "improved mood" or "fewer headaches", the research was not used in any calculations, but it was included as a qualitative benefit to help guide the decision-making process. This literature search was not exhaustive or complete due to the inclusion of dozens of individual topics. Over 700 studies and reports were screened and more than two hundred of these were incorporated into this work.

During the computer-based literature search the initial searches queried results from 2002 to present. Prior to 2002 little was known about intrinsically photosensitive retinal ganglion cells (ipRGCs) and their impact on human circadian rhythms and wellness (Figueiro et al., 2018). Since the discovery of ipRGCs much of the newer lighting research incorporates spectral power distribution, color tuning, LEDs, advanced solar films and advanced lighting controls, which all play an essential part in lighting features in the WBSv2. Older research typically focused on incandescent, compact fluorescent or fluorescent light sources and correlated color temperatures (CCT) rather than spectral power distribution. These older studies often measured typing speed on typewriters and used paper-based tasks or highly reflective CRT screens for lighting productivity related research. Office work has changed significantly in the past two decades and researchers have learned a tremendous amount about the biological effects of light. Incorporating older studies may skew the results and minimize the actual benefits of high quality lighting conditions. If few or no appropriate contemporary studies were available, older studies were used to help fill in the research gaps.

Building the Base Model

In order to develop an estimate of the costs to upgrade a building from a code compliant building to being able to achieve each of the lighting features of the WBSv2, a building was selected to use as a model. The building was analyzed to determine if it met features of the WBSv2. If the building did not meet the requirements of each feature, quotes were obtained from a major lighting manufacturer or manufacturer's representative in order to obtain realistic pricing for each upgrade.

A well-known architecture, design and planning firm in Washington DC gave permission to use their office as a base-model for calculating the costs and benefits of implementing each feature of the WBSv2. Representatives for the firm prefer that the business's name not be highlighted in research projects, therefore the office space will be referred to as either the "model office space" or MOS. Architectural drawings, lighting fixture cut sheets, a Revit Building Information Model (BIM), a lighting plan, daylight analysis software and multiple site visits helped evaluate whether the existing building met the criteria for each WBSv2 feature and, if not, determine what was necessary in order to achieve them.

The MOS was located on two floors of an eleven-story building in Washington DC that was originally built in 1974. This office renovation was completed in 2013. There were approximately 215 employee workstations spread across two floors. This space was selected because it met several criteria:

1. The MOS was approximately 45,000 square feet which is similar in size to the U.S. Department of Energy's reference model representing a medium sized office building (53,628 square feet) (U.S. Department of Energy, 2012). The location enabled me to conduct multiple research site visits.
2. The MOS was located in a Class A office building with common fixtures and lighting controls.
3. The firm provided access to Revit BIM files that enabled detailed analyses of daylight, artificial lighting, windows and interior conditions. This information was necessary in order to calculate the cost to upgrade the office space to meet the WBSv2 lighting features.
4. Lighting controls system data and a bill of materials was available.
5. Permission was granted to use the office as a model for this study
6. The MOS was similar to the types of spaces that might have been considered for WBSv2 Certification if the standard had existed at the time. Many of the same lighting features that are now part of the WBSv2 were implemented in the MOS because some of the benefits of many of these lighting conditions have been known for decades.

Costs of Upgrading Existing Building to Meet WBSv2 Lighting Features

Costs of upgrading the MOS design to a design that met each feature of the WBSv2 were based on actual prices in Washington, DC. The MOS achieved several features automatically and in some cases it was able to achieve a feature via multiple pathways or options. Actual budget quotes and estimates for materials from major lighting and controls manufacturers and manufacturer's representatives were used to develop cost estimates for upgrades.

This thesis incorporated several pre and post occupancy studies of buildings that have achieved WBS Certification, LEED and/or other green building certifications, and lighting and wellness upgrades in order to show how the changes impacted productivity. To supplement the pre/post occupancy study data relating to productivity benefits, existing scientific literature was analyzed to develop a median value for the estimated impacts that specific lighting/controls improvements have on productivity.

For some of the features there was a significant cost to implement a feature while other features could be achieved at little to no additional cost. A focus of this research was to determine the upfront cost of upgrading a building in order to achieve WBSV2 lighting features, therefore if a piece of equipment needed to be swapped to achieve a feature, labor was not included. If a feature required labor above and beyond the original design to implement, then labor pricing was included.

Modeling Assumptions

The model was based on an existing commercial office space. Many of the results of this study will apply to other building types but this model does not consider dwelling units, residences, retail, etc. This model was designed to serve as a ballpark reference. Due to the specific design characteristics of this building, it automatically met certain WBS features that a building with other design characteristics may not have achieved. For instance, a tall, narrow building with a glass curtain wall may easily meet Feature L05 Enhanced Daylight Access, without any modification to the design, whereas a short deep building with small windows may not be able to meet L05 without changing the entire building design. This model does not consider changing the size and massing of a building in order to achieve WELL features. This model assumed that the project would already be using the services of a lighting designer who would take into consideration the light levels, tasks, ages of occupants, etc. The costs of certification are not considered in this thesis because it is not feasible to separate the costs of lighting certification from the other 9 concept areas that make up the WBSv2.

The spreadsheet model used to calculate estimated benefits assumed 151 square feet per employee because that was the projected average number of square feet per employee in North America in 2017 (Mehigan, 2016).

Quantifying the Value of Increased Worker Productivity

Worker productivity refers to the measure of output produced per employee over a specified period. In order to determine a quantitative value for an increase in performance and productivity, I used the salary and performance data used by MacNaughton et al. (2015) in a study that included the economic implications of increasing ventilation in office buildings:

> Data on salaries for various occupations was obtained from the Bureau of Labor Statistics (BLS). The 10th, 25th, 50th, 75th and 90th percentile

> salaries for management, business and financial operations, office and administrative support, computer and mathematical, architecture and engineering, legal, and sales occupations from May 2014 were used for analyses. These occupation groups were selected to represent the U.S. office workforce and accounts for 57 million of the 135 million employments listed by BLS. Using averages weighted by the number of employments in each occupation group, mean salaries were computed for each percentile. The 90th percentile was missing for management and legal occupations, so it was excluded from subsequent analyses… several assumptions were made to derive the economic benefits. First, we assume that the population of knowledge workers that took the cognitive testing was representative of the U.S. office workforce. 20% of that group held management positions compared to 12% in the BLS data, and 60% had professional occupations compared to 50% in the BLS data. Second, we assume a one-percentile change in cognitive function corresponds to a one-percentile change in value as an employee (e.g., someone who scores in the 62nd percentile is salaried at the 62nd percentile). Previous work with the SMS tool has shown high correlations (>0.6) between cognitive scores and salary (MacNaughton et al., 2015, p. 14,714).

Based on the salary data and assumptions listed above, a salary of $81,250 was used to calculate average productivity benefits. MacNaughton et al. (2015) determined that a 1% improvement in cognitive performance is equal to an $812.50 increase in value to an employer. Because not all work tasks require high levels of cognitive performance, I assumed that a 1% increase in cognitive performance resulted in a 0.5% increase in productivity, valued at $406.25. Additionally, a 1% increase in overall worker performance was considered the same as a 1% increase in productivity.

Value of Controlling Solar Glare

Uncontrolled solar glare has a tremendous negative impact on worker productivity and can reduce productivity as much as 21% while working in glare conditions (California Energy Commission, 2003). However, the impact only occurs at certain times of the day or year and it only affects a portion of building occupants. The calculation of the loss of productivity due to solar glare this study was based on the following assumptions:

1. Based on an \$81,250 average annual salary discussed above, the hourly rate would be \$39.06 per hour.
2. Because every building has different envelope, glazing, weather and interior conditions and there is no general rule of thumb for calculating solar glare, the MOS's real world conditions were used to calculate the cost of glare. An analysis was performed using both Revit's Insight Plug-in and Light Stanza's web platform, and the MOS was determined to have an annual sunlight exposure ($ASE_{1000,250}$) for 4% of the model office's total building area over the course of a year (Figure 11). This means 4% of the total area exceeded 1000 lux for at least 250 hours per year. As such, it was assumed that 4% of the workers were exposed to glare conditions for 12.5% (250 hours of glare/2000 work hours) of the work year. Once the estimate for reduced productivity due to glare was established, it was multiplied by either \$812.50 for measures of productivity, or by \$402.25 for measures of cognitive performance.

Value of Sleep

Gibson and Shrader reported that a one-hour increase in long-term average sleep increases wages by 16%, equivalent to more than one additional year of education (Gibson & Shrader, 2014). If productivity increases linearly with each additional minute of long term, average sleep, 46 minutes of extra sleep for workers with windows would be worth 12.32% of an employee's salary or \$10,010 for an average office worker. The

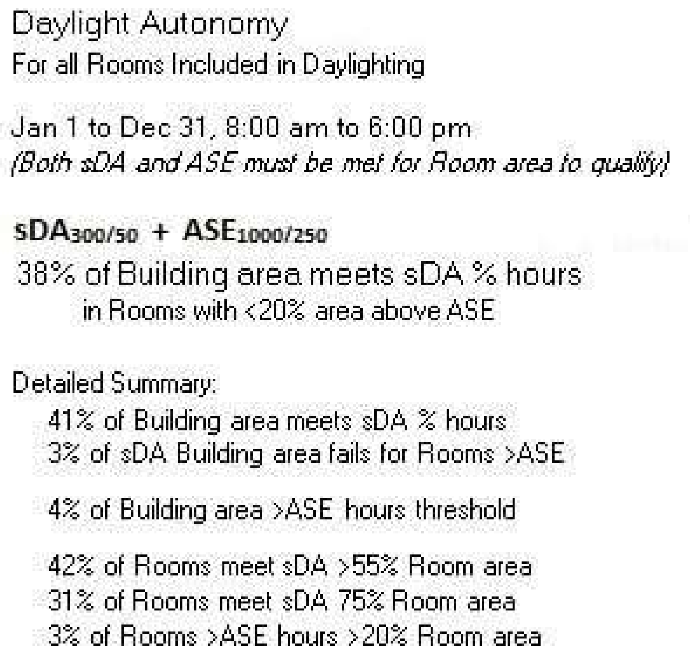


Figure 11. Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) analysis of model building (Screen capture from Revit Insight Plugin).

extra sleep for workers with windows is likely to lead toward improved performance and increased productivity.

Other studies estimate the value of sleep to an employer to be much lower. Rosekind et al. (2010) reported that fatigue-related productivity losses were estimated to cost businesses $1,967 per employee annually. This figure was determined by comparing a group of good sleepers against a group of insomniacs and monitoring the productivity of each group. The mean total sleep for the group of insomniacs was six hours per night while the mean total sleep for the good sleep group was six hours and forty two minutes per night (Rosekind et al., 2010). Dividing the $1,967 productivity losses by the sleep difference of 42 minutes yields a per-minute value of average annual sleep being worth

$46.83 per year. This value was used to calculate the economic benefits when research shows lighting impacts sleep duration.

Value of Reduced Absenteeism

Absenteeism is an absence from work without a good reason. Absenteeism is costly and disruptive for businesses and the rate of absenteeism has been steadily increasing (Kocakulah, Kelley, Mitchell, & Ruggieri, 2016). The U.S. Department of Labor reported that absenteeism costs private employers $2,074 per employee per year and costs public sector employers $2,502 per employee per year (Browning, Garvin, Fox, & Cook, 2012). The Centers for Disease Control Foundation reported that absenteeism costs employers $1,685 per employee per year (CDC Foundation, 2015). For purposes of this thesis, the difference between the private employer cost from the U.S. Department of Labor ($2074) and the CDC foundation cost ($1,685) was split and an absenteeism cost to employers of $1,879.50 per employee per year was used in financial impact calculations for absenteeism.

Impact of Productivity Improvements

Research relating to productivity improvements incorporated into this thesis are predominantly given in percentages. These values are often the result of measuring the productivity of workers working under poor lighting conditions that are realistically encountered in office buildings and then comparing the results to workers working under improved lighting conditions. The mean values of productivity increases listed in this thesis typically do not affect all workers in the building. For instance, if the general overhead lighting is a very poor 15 foot-candles throughout a building, workers would likely see a significant improvement if lighting were upgraded to 100 foot-candles. When calculating the financial impact this improvement could have, it is important to subtract the employees working near windows because they may already be exposed to more than 150 foot-candles from natural daylight and they are unlikely to experience the same productivity improvements as workers in poor lighting conditions. Since each feature of the WBSv2 affects a different portion of a building and a different number of workers, assumptions were listed at the end of each feature explaining how the financial benefits were calculated.

Analyzing Benefits Associated with Feature of the WBSv2

An analysis was conducted to determine whether the MOS automatically achieved all or part of each feature. Each feature was then broken down into the major luminous parameters the feature attempts to address (Table 2).

If available, results of previous research reporting on productivity improvements related to each of the luminous parameters was presented. An analysis as to how closely the feature matches the conditions of previous scientific studies was conducted.

The results for each of the WBSv2 lighting features show a compilation of studies and scientific literature quantifying the financial impact of specific lighting related conditions. In some cases, the results can be added to one another for a cumulative effect, while in other cases if one condition has already been met there will be little to no improvement by achieving a related condition. For instance, if there are productivity benefits of increasing the luminance level in poorly lit spaces a worker may experience

Table 2. Lighting parameters for each WBSv2 feature that may affect productivity.

Feature	Parameters in each feature that may affect productivity
L01	Access to windows / Views to the outside / Biophilia Circadian lighting / Daylight Educational component
L02	Lighting for visual acuity Age specific lighting
L03	Circadian lighting (Overlaps with Feature L01)
L04	Visual comfort Reducing solar glare Reducing glare from electric light sources
L05	Daylight (Overlaps with Feature L01)
L06	Luminance balance Visual comfort (Overlaps with Feature L04) Slow light level fade rate
L07	Color rendering / Full spectrum lighting Managing low frequency flicker
L08	Tunable lighting / Adjustable correlated color temperature Personal control Light color

productivity improvements by increasing the electric light level. However, if an employee has a large window in their office that provides high levels of daylight throughout the day, that employee will already be receiving the benefit of brighter light and increasing the electric light level will have very little impact on productivity.

Many of the studies show the results of going from working under a poor or average lighting condition to working under an improved lighting condition. In most office buildings there will be areas with varying levels of lighting conditions ranging from poor to excellent. The results of these studies will therefore only apply to the workers who would be exposed to the poor study condition such as workers in windowless offices, or workers exposed to solar glare, etc.

The lighting parameters in some studies overlap with one another. For instance, there are several that analyze the impact of windows and views on productivity. It is likely that anyone with a view through a window will also be benefitting from access to natural daylight. However, there are separate studies that show the impact of natural daylight on productivity. For this thesis, research has been siloed to compare results of similar studies even though the underlying lighting parameter may be similar in more than one silo.

In order to illustrate the impact a feature may have on overall worker productivity, studies that report the following topics known to improve productivity was included in the productivity analysis:

1. Improved performance
2. Increased cognitive performance
3. Longer sleep duration
4. Reduced absenteeism
5. Additional time spent on primary work tasks
6. Increased sales/calls/other worker output metrics

In addition to including studies reporting quantitative productivity related benefits of lighting, dozens of qualitative ancillary benefits reported in scientific literature were included as well. The ancillary benefits listed in this paper were not specifically searched for; rather they were uncovered over the course of research into the quantitative productivity related benefits of lighting. Although by no means exhaustive, the inclusion of these results will give designers and decision makers a more complete understanding of the potential impact of each lighting feature. In order to better visualize the ancillary benefits, individual benefits were grouped into categories (Table 3).

Table 3. Ancillary benefits reported due to improved lighting conditions.

Financial	**Health**	**Well-being**	**Cognitive Function**	**Performance**	**Safety**
Financial savings, lower healthcare costs, lower employee turnover, growth in business, improved sales	Lower cortisol levels, improved glucose metabolism, reduced fatigue, lower BMI, fewer headaches, decreased eye strain	Reduced stress, improved mood, higher levels of satisfaction, lower depression scores, feelings of vitality, fewer workplace complaints, visual comfort	Improved concentration, fewer errors, improved memory, increased attention span, increased alertness	Higher energy levels, improved performance, greater productivity, reduced fatigue, faster reaction times	Improved safety, lower safety risks, fewer accidents

Chapter III

Results

Table 4 shows the results of post occupancy field studies where workers moved from traditional buildings into either "green" buildings or workspaces with significantly improved IEQ. The IEQ improvements in these studies were primarily lighting, indoor air quality, thermal comfort, acoustics and personal controls.

Table 4. Field studies of worker productivity for workers moving from traditional buildings to green buildings or buildings with improved IEQ (for details see Appendix 1)

Study	Productivity Increase Converted to Dollars	Reference
ASID HQ Post Occupancy	$13,000.00	(Chung, 2017)
Lockheed Renovation	$12,187.50	(Edwards & Torcellini, 2002)
West Bend Insurance	$13,000.00	(Romm and Browning 1994)
Niemela Renovations	$7,393.75	(Niemela et al., 2002)
Conventional to LEED Study	$2,112.50	(Singh et al., 2010)
Study of 33 Green Buildings	$6,946.00	(Kats, 2003)
Survey of Green Buildings	$6,200.00	(Miller et al., 2009)
MacNaughton et al.	$10,725.00	(MacNaughton et al., 2017)

The results of reported productivity increases from improved IEQ conditions in the workspace range from $2,112.50 to $13,000 per worker per year with a median increase of $9,059.38 and an average productivity increase of $8,642.98 per employee per year (Table 4). Figure 12 plots the distribution of productivity increases for the eight field studies of worker productivity.

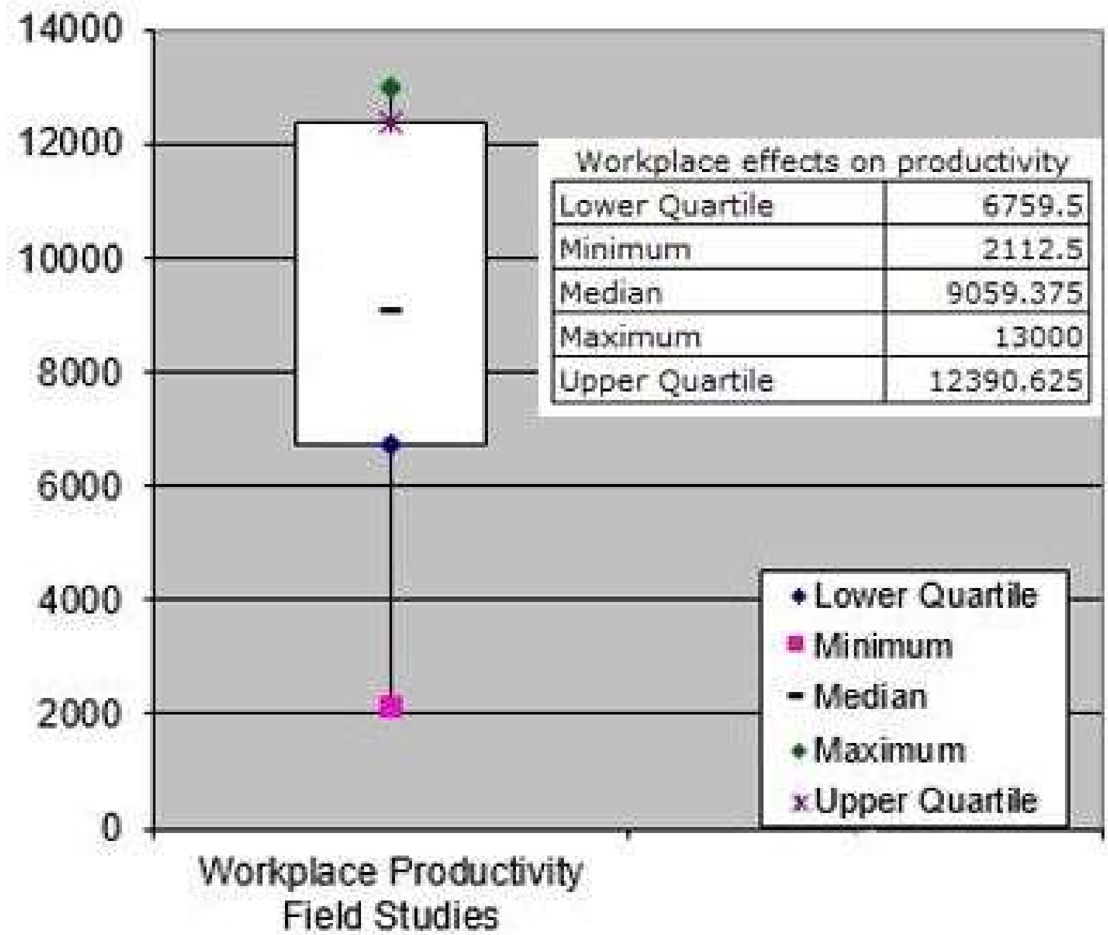


Figure 12. Distribution of measured productivity increases after employees moved from a conventional workspace to workspaces with improved IEQ.

Productivity Related Laboratory Studies and Field Research

While Table 4 shows the results of long-term real-world productivity gains from field studies of workers who moved into buildings with better IEQ, Table 5 shows lab study estimates of productivity gains due to improved IEQ conditions. Many of these results are based on laboratory studies while some were based on short-term field studies where specific environmental conditions were controlled. It is worth noting that on average, the laboratory study estimates of potential productivity improvements in Table 4 are more conservative than the actual measured productivity increases from field studies in Table 5. It is possible that some of the benefits of working in offices with improved IEQ may not manifest themselves for weeks or months, and these delayed improvements might be difficult to measure in a laboratory setting.

Table 5. Estimated potential worker productivity increases due to improved IEQ in office buildings (for details see Appendix 1).

Study	Productivity Increase	Reference
GSA Workplace Study	$2,437.50	(General Services Administration, 2006)
Wyon	$8,125.00	(Wyon, 1996)
Pollard	$7,312.50	(Clements-Croome, 2006)
Roelofsen	$8,125.00	(Roelofsen, 2002)
Lomonaco et al.	$7,312.50	(Lomonaco, C. and Miller, D., 1997)
CA Energy Commission	$2,843.75	(CA Energy Commission, 2003)
Kroner et al.	$2,437.50	(Kroner et al., 1992)
Leyten	$10,156.25	(Leyten & Boestra, 2003)
Lorsch	$8,125.00	(Lorsch, 1994)
CBPD Analysis of 13 Studies	$8,531.25	(Loftness & Hartkopf, 2003)
Kats	$2,234.38	(Kats, 2003)
AT Kearney	$8,125.00	(AT Kearney, 2015)
Fisk and Rosenfeld	$2,234.38	(Fisk and Rosenfeld, 1997)

The results of reported productivity increases from improved IEQ conditions in the workspace range from $2,234 to $10,156 with a median increase of $7,312 and a mean increase of $6,000 per employee per year. Figure 13 plots the distribution of the 13 productivity studies shown in Table 5.

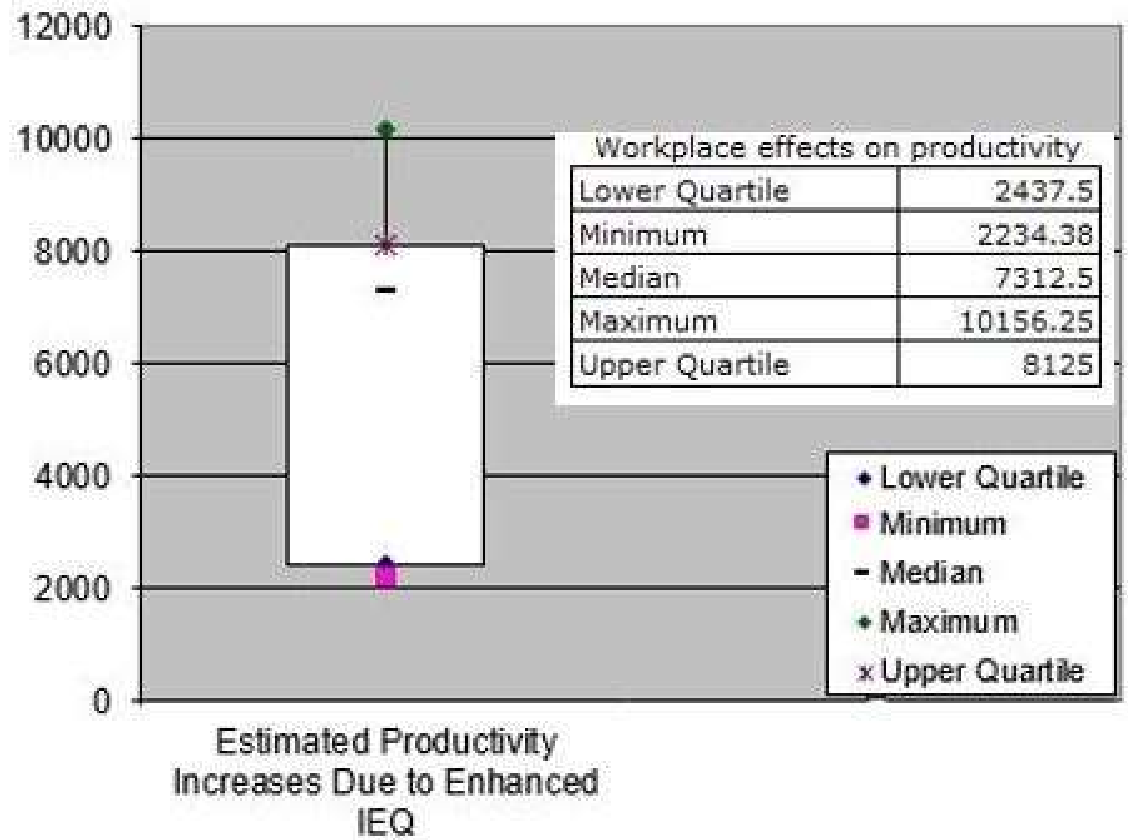


Figure 13. Distribution of estimated worker productivity increases due to improved IEQ in office buildings.

Productivity studies specifically related to lighting were compiled and analyzed (Table 6). Although these studies did not use the specific parameters required by the WBSv2 they illustrate the potential impact lighting can have on worker productivity (for details see Appendix 1). The results range from a low of $3,250 to a high of $10,562 with a median of $7,719 and a mean productivity increase of $7,722 per employee per year (Figure 14).

Table 6. Studies showing the estimated impact of lighting improvements on worker productivity.

Study	Productivity Increase Converted to Dollars	Reference
Heschong et al., 2002	$9,628.13	(Heschong et al., 2002)
Kaczmarczyk and Morris	$9,750.00	(Kaczmarczyk & Morris, 2002)
Pennsylvania Power	$10,562.50	(NIST, 1995)
Abdou	$7,312.50	(Abdou, 1997)
Post Office Renovation	$4,875.00	(Romm, 1994)
Bommel et al.	$6,500.00	(Bommel et al., 2002)
NLB Lighting Renovation 1	$8,125.00	(Abdou, 1997)
NLB Lighting Renovation 2	$3,250.00	(Abdou, 1997)
Stenzel Study	$6,175.00	(Stenzel 1962)
CBPD 1	$10,562.50	(Loftness & Hartkopf, 2003)
CBPD 2	$6,581.25	(Loftness & Hartkopf, 2003)
Heschong/Mahone	$9,343.75	(Heschong, 1999)

To put the annual costs of lighting into perspective with the potential productivity increases listed above, a typical business spends approximately $75.00 per year per employee for lighting related expenses based on 50 cents per square foot for annual lighting expenses, and an average of 151 square feet per employee (Abdou, 1997). If employees are working under poor lighting conditions, for an extra $75 per employee a business could potentially double the lighting quality and reap $7,722 in productivity related gains for each employee each year.

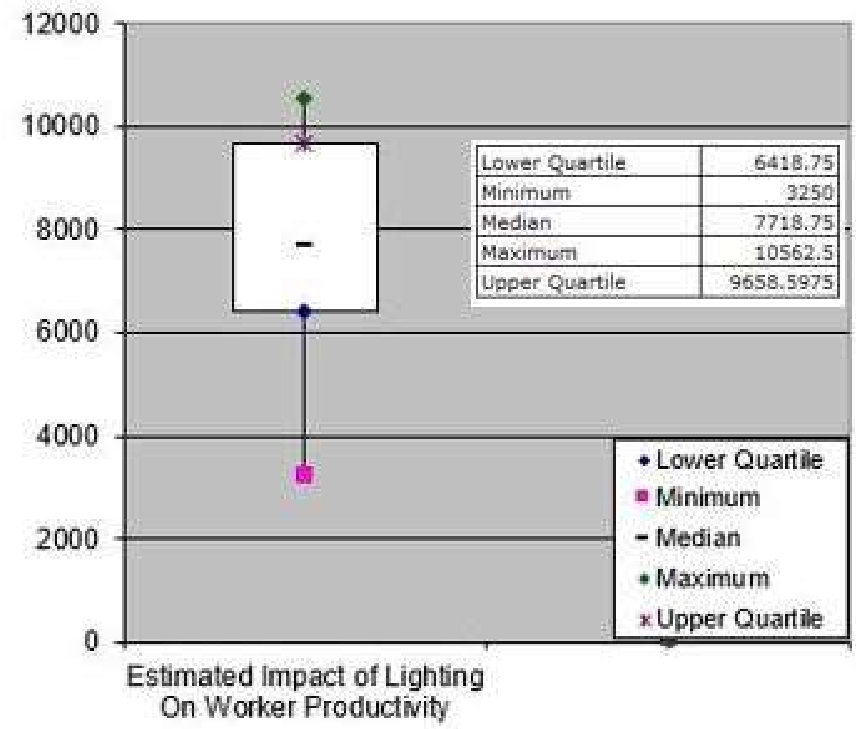


Figure 14. Distribution of estimated worker productivity increases due to improved lighting conditions in office buildings.

WBSv2 Lighting Features and Associated Research

With research indicating that a properly designed luminous environment may increase worker productivity between $3,250 and $10,562 per employee per year, a high-quality lighting and controls design should be considered as a potential means to reduce business operating costs. Many designers and building owners seeking to maximize the performance and productivity of their workforce are likely to refer to the WBS for design guidance. For these building professionals it would be helpful to know whether the WBS lighting features are likely to capture a large percentage of the potential productivity improvements listed previously in Table 6. The following section details the results of the cost/benefit analysis of each feature of the WBSv2 in the MOS.

Feature L01 – Light Exposure and Education

This mandatory feature was developed to ensure building occupants are exposed to adequate levels of daylight throughout the day. The feature also requires building owners to try to educate workers on the importance of circadian lighting so they seek appropriate lighting outside of work in order to improve their health and well-being. Table 7 shows the requirements of Feature L01 as well as the results of the model office space analysis.

Table 7. Requirements of Feature L01 and results of model analysis.

L01 Light Exposure and Education (Precondition)	**Model Office Space Results**			
Part 1. Ensure Indoor Light Exposure	Legend	Model achieves feature with no changes necessary	Model achieves feature at little to no cost and effort	Model cannot achieve feature without considerable cost or effort
Choose 1 of the following 3 options:				
Option 1. Daylight in all spaces: Achieve at least 1	Project achieved sDA 300/50% for 36% of the total floor area, exceeding the minimum requirement by a considerable margin.			
A. Spatial Daylight Autonomy of sDA 200,40% is achieved for at least 30% of regularly occupied space.				
B. 30% of all workstations are within 20 feet of transparent envelope glazing. Visible light transmittance (VLT) of transparent glazing is greater than 40%.	Project meets this requirement. Over 70% of workstations are located within 20 feet of a window with a VLT of 85%.			
C. Transparent envelope glazing area is no less than 7% of the floor area for each floor level. VLT of envelope glazing is greater than 40%.	Project does not meet this option because the 1st floor windows only equal 4.4% of the entire floor area. The 2nd floor exceeds 7%.			
Option 2. Daylight in common spaces:				
Regular building occupants have unrestricted access to indoor common spaces with unassigned seating that accommodates at least 15% of regular building occupants at any given time. The spaces are located within the project boundary and each meet at least one of the following requirements:				

A. Spatial Daylight Autonomy of $sDA_{300, 50\%}$ is achieved for at least 70% of the space.	The model space achieves this option without needing any changes. Approximately 36% of the entire floor area achieves and $sDA_{300,50\%}$ and over 70% of workstations are within 20 feet of a window.
B. 70% of all seating in the space is within 16 feet of transparent envelope glazing with views to the exterior. VLT of envelope glazing is greater than 40%.	The model project achieves this option without requiring any changes. (See above) VLT is 85%.
C. Transparent envelope glazing area is no less than 10% of gross internal floor area of the space. Visible Light Transmittance (VLT) of envelope glazing is greater than 40%.	The project meets this requirement. The total floor area is 45,349 square feet and the windows are 5,112 square feet for a total of 11.27% of floor area. VLT is 85%
Option 3. Electric light in regularly occupied space	Project achieved one point as designed for Feature L03.
Achieve at least 1 point in Feature L03: Circadian Lighting Design.	
Part 2. Promote lighting education	
Projects provide educational resources on circadian rhythm, sleep hygiene, age-related increase in light requirements and/or importance of daylight exposure on circadian and mental health that meet at least two of the following requirements:	
A. Educational signage is placed at high traffic points around the space.	The project can meet this at little cost and very little effort.
B. Newsletters or newsletter entries are issued to all occupants at least every quarter.	The project can meet this at little cost and very little effort.
C. At least two of the resources provided for Part 2: Health and Wellness Education of Feature C01: Health and Wellness Awareness cover information on circadian rhythm, sleep hygiene, age-related increase in light requirements and/or importance of daylight exposure to circadian and mental health.	The project can meet this at little cost and very little effort.

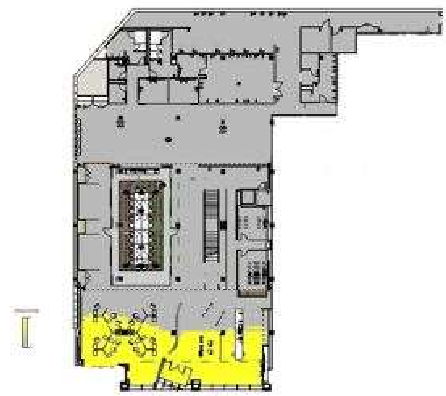
Feature L01 Model Summary

The MOS meets this mandatory feature though a number of options without requiring any significant changes or expenses. To meet Part 1 of this requirement the

MOS only needed to meet one of seven pathways, but it was able to achieve six. For Part 2 the MOS can achieve the requirements by providing literature relating to health and wellness on the topics listed above, either physically or digitally, by placing educational signage at high traffic areas around the space, and/or issuing newsletter entries relating to the impact of light on health to all building occupants at least quarterly.

Figure 15 shows a daylight model created using Autodesk Revit 2019 with the Revit Insight Plug-in. The MOS achieves spatial daylight autonomy with a minimum of 300 lux for at least 50% of the hours between 8:00am and 6:00pm. The Revit model enabled measurements to be taken from the workstations to the windows in order to verify the percentage of workstations near windows as well as the floor to window area ratios.

The two options in Feature L01 that were not met automatically with the MOS were Option 1C and Option 3. Option 1C requires that each floor have window area that exceeds 7% of the floor area. The MOS met this feature for the second floor but did not meet it for the first floor, as the window area totaled approximately 4% of gross internal floor area. The MOS cannot meet this feature without adding windows and changing the building façade. Because the MOS met several other pathways to achieve this feature, the cost of adding windows was not calculated. The MOS also met the requirements of Option 3 by achieving a point under Feature L03 Circadian Lighting Design (see Feature L03 for more information).



First Floor

Second Floor

Figure 15. Daylight autonomy analysis of model office space.

In order to qualify for this feature, two minor changes need to be made in order to achieve two of the three options in Part 2. For the first option, wellness literature could be downloaded for free from the Internet and made available online or via employee email. The cost of labor is estimated to be less than $100. For the second option a few small lighting education signs could be printed on foam core and placed near high traffic points. The signs could be created for less than $200 and the labor is likely to be less than $100. The MOS could achieve feature L01 for less than $400.

While calculating the value of increased productivity and improved performance can be difficult with a wide range of values, measuring absenteeism is more straightforward. For field studies it is easy to analyze the number of missed workdays before and after a lighting parameter changes. Several studies have evaluated the impact of windows, daylight and views on absenteeism (Table 8).

Table 8. The effect of daylight and views on absenteeism per employee per year (for details see Appendix 1).

Study	Savings from reduced absenteeism	References
ING Bank	$281.93	(Edwards et al., 2002)
Lockheed Martin	$281.93	(Romm and Browning, 1994)
VeriFone	$265.61	(Edwards & Torcellini, 2002)
Benton	$281.93	(Loftness & Hartkopf, 2003)
Thayer	$281.93	(Loftness et al., 2013)
Rocky Mountain Institute	$281.93	(Edwards et al., 2002)
AT Kearney	$18.80	(AT Kearney, 2015)
Elzeyadi, 2011	$240.20	(Elzeyadi, 2011)
Elzeyadi, 2011	$624.96	(Elzeyadi, 2011)
Elzeyadi, 2011	$61.08	(Elzeyadi, 2011)
Elzeyadi et al., 2017	$187.95	(Elzeyadi et al., 2017)

Figure 16 shows the distribution of results from absenteeism studies related to daylight and views in office buildings. The results range from \$18.80 to \$624.26 with a median of \$282. From these studies it can be concluded that workers who are exposed to daylight and views average approximately 15% fewer missed workdays saving employers an average of \$255 per employee per year compared to employees without daylight and views.

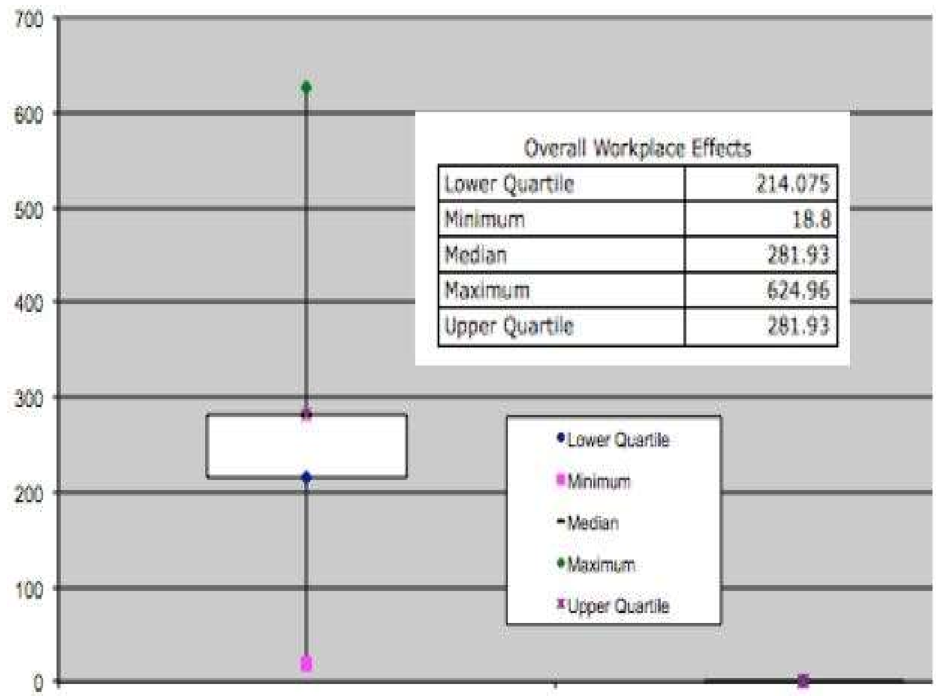


Figure 16. Distribution of value estimates of reduced absenteeism due to daylight and views.

The impact of windows and views appears to be quite large. The value of the estimated productivity increase for workers with views and access to daylight compared to workers with no views or access to daylight ranged from $325-$10,000 (Table 9).

Table 9. Estimated financial benefits of windows and views on worker productivity (Appendix 1).

Windows & Views	Productivity Increase Converted to Dollars	Reference
Boubekri et al.	$2,154.18	(Boubekri et al., 2014)
Lighting Research Center	$10,000.00	(Figueiro et al., 2002)
Heschong Schools	$7,718.75	(Heschong, 1999)
Sterling and Sterling	$2,060.00	(Loftness & Hartkopf, 2003)
Department of Energy HQ	$325.00	(Loftness & Hartkopf, 2003)
CA Energy Commission	$7,312.50	(CA Energy Commission, 2003)
CA Energy Commission	$7,109.38	(CA Energy Commission, 2003)
PNNL, U Illinois 2011	$8,125.00	(Edwards et al., 2002)

Figure 17 shows the distribution of results from studies estimating productivity improvements due to worker access to windows and views. The results range from $325.00 to $10,000 with a median of $7,211. Based on these studies it can be concluded that on average, for employees who move from windowless workspaces to workspaces with windows and views it will lead to increased productivity worth $5,601 per employee per year.

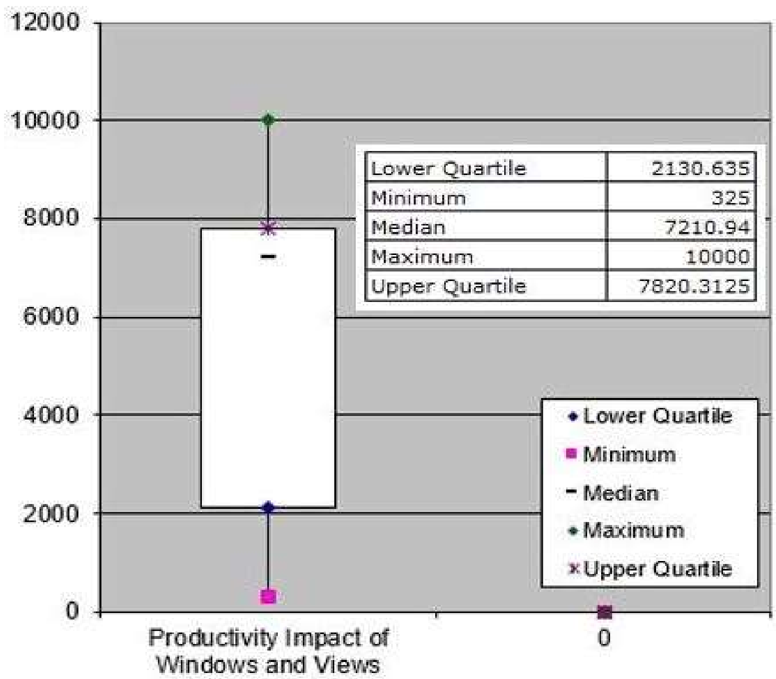


Figure 17. Distribution of research estimates of productivity improvements due to worker access to windows and views.

Daylight and circadian lighting have a large impact on worker productivity (Table 10). The estimated productivity increase for workers exposed to daylight or high levels of circadian effective light compared to workers with no daylight and low levels of circadian effective light average $5,735 (Appendix 1).

Table 10. Estimated financial benefits of daylight and circadian lighting on worker productivity.

Daylight and Circadian Lighting	Productivity Increase Converted to Dollars	Reference
Verifone/Romm	$4,062.50	(Loftness & Hartkopf, 2003)
Wilkins	$4,062.50	(Wilkins, 1995)
Heschong	$9,343.75	(Heschong, 1999)
AT Kearney	$934.38	(AT Kearney, 2015)
Figueiro	$12,187.50	(Figueiro 2002)
Al-Ashwal	$8,125.00	(Al-Ashwal et al., 2018)
Boubekri et al.	$2,154.18	(Boubekri et al., 2014).
Carnegie Melon	$226.00	(Loftness et al., 2013)
Obayashi	$8,125.00	(Obayashi et al., 2007)
PNNL, U Illinois 2011	$8,125.00	(Edwards et al., 2002)

Figure 18 shows the distribution of results from studies estimating productivity improvements due to worker access to daylight and/or circadian lighting. The results ranged from $226.00 to $12,187 with a median of $4,062. Based on this research it can be concluded that providing access to high levels of daylight and/or circadian effective light to employees who previously had no daylight and poor levels of circadian effective light in their workspaces can lead to an average productivity increase worth $5,468.98 per employee per year.

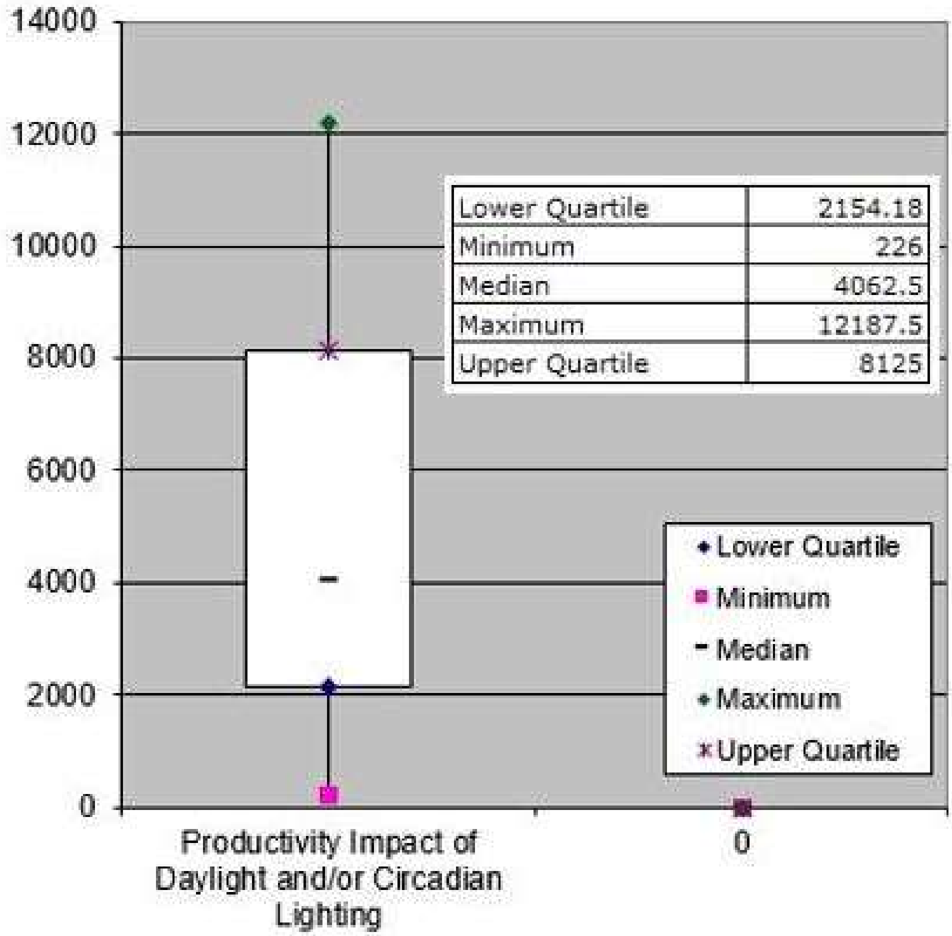


Figure 18. Distribution of research estimates quantifying productivity improvements due to worker access to daylight and/or circadian lighting.

In addition to the quantitative analysis of the benefits of windows and views and daylight/circadian lighting, the research used for this thesis reported several additional ancillary qualitative benefits. For windows and views there were 13 studies and reports that listed ancillary benefits that were not included in the quantitative analysis above. Table 11 shows these additional benefits (Appendix 1).

Table 11. Instances of ancillary benefits of windows and views reported in scientific literature used for this thesis.

Study	Financial	Well-Being	Health	Safety	Cognitive Function	Performance	Reference
Large field study of open offices	X						(Veitch et al., 2003)
Kaplan		X					(Clements-Croome, 2006)
Carnegie Mellon			X				(Edwards et al., 2002)
Yildirim et al.	X						(Yildirim et al., 2007)
Boubekri et al.	X	X	X X X X X	X	X X	XXXX	(Boubekri et al., 2014)
Kaplan		X X					(Clements-Croome, 2006)
Boyce, et al.	X	X	X				(Boyce et al., 2003)
Aries et al.	X	X	X X			X	(Aries et al, 2010)
CA Energy Commission			X XXX		X	X	(CA Energy Commission, 2003)
Abdou	X	X	X			X	(Abdou, 1997)
Ruck			XXX			X	(Abdou, 1997
Elzeyadi						X	(Elzeyadi, 2011)
Boyce, et al.					X		(Boyce et al., 2003)
	6	7	17	1	4	9	

For daylight and/or circadian lighting there were 16 studies used for this thesis that listed additional ancillary benefits not included in the quantitative analysis above (Table 12).

Figure 19 shows the distribution of the ancillary benefits reported for windows and views, as well as daylighting and/or circadian lighting. The similar patterns may be the result of windows and views also providing daylight/circadian lighting and many workers who have daylight also have views.

Table 12. Instances of ancillary benefits of daylight and circadian lighting reported in scientific literature used for this thesis (Appendix 1).

Study	Financial	Well-Being	Health	Safety	Cognitive Function	Performance	Reference
Franta and Anstead	X		X X			X	(Franta & Anstead, 1994)
Boyce et al.	X				X X	X X	(Boyce et al., 2003)
Yildirim et al.	X	X					(Yildirim et al., 2007)
Elzeyadi			X X X			XXX	(Elzeyadi, 2011)
CA Energy Commission					X X		(CA Energy Commission, 2003)
Rahman et al.						X	(Rahman et al., 2014)
Figueiro et al.		X					(Figueiro et al., 2017)
Shishegar & Boubekri	X	XX	XX		X XX	XXXX	(Shishegar & Boubekri, 2016)
Edwards et al.	X						(Edwards et al., 2002)
Wilks et al.			X				(Boyce et al., 2003.)
UK Health & Safety Executive			X	X			(Great Britain Health and Safety Executive, 2002)
Rocky Mtn Institute	X						(Edwards et al., 2002)
Figueiro et al.		X	XXXX		X	X	(Figueiro et al., 2018)
Bommel et al.		X			X		(Bommel et al., 2002)
Boyce, et al.		X	X			X	(Boyce et al., 2003)
Sahin et al.						X	(Sahin et al., 2014)
	6	7	14	1	9	14	

Feature L01 Analysis of Results

The research showed that having access to windows and views is worth an average of $5,601 per employee per year to an employer. Having access to daylight and/or circadian lighting is worth an average of $5,469 per employee per year.   It is impossible to separate the effects or daylight versus views for people in windowed offices. If a subject has a window with a view then they also have access to daylight.

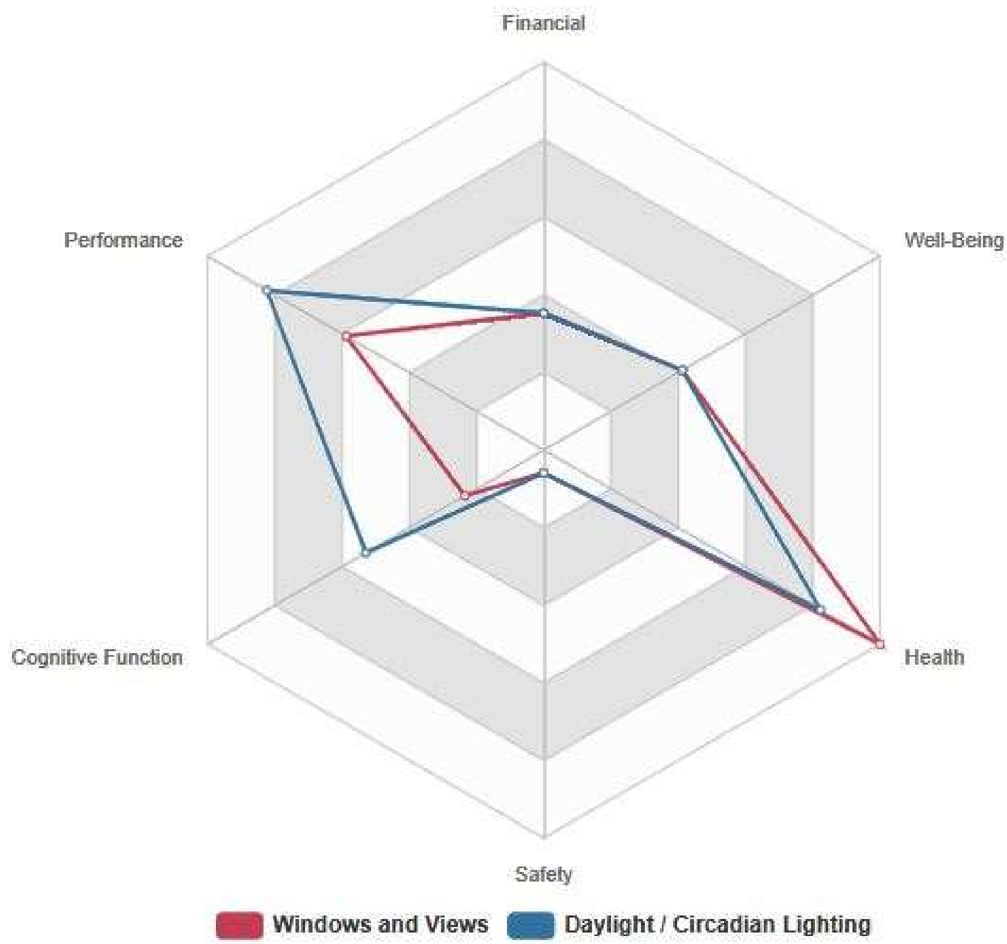


Figure 19. Qualitative benefits of windows and views and daylight/circadian lighting reported in scientific literature (Appendix 1).

Due to the overlap the results of the two groups of studies will be averaged together for this thesis to come up with a financial benefit of $5,535 per employee per year for each affected employee. Figure 19 indicates that the ancillary benefits are very similar for both windows and views and daylight/circadian lighting.

The existing layout of the MOS and the large windows allowed the original design to achieve Feature L01 as built. Because the original design already met the requirements of Feature L01 the benefits of the feature cannot be applied to the majority of workers in the space. However, an analysis of the current space shows there are opportunities to move employees from windowless areas into spaces with windows in order to capitalize on the benefits of windows and daylight. The current design of the model office has 29 employees working on the first floor in an area with no access to windows or views. There is also an area on the second floor with a southern and western exposure that is currently being used as conference rooms. Some of the conference space could be moved to the first floor and the staff could be moved to the second floor. Figure 20 shows the layout of each of these spaces.

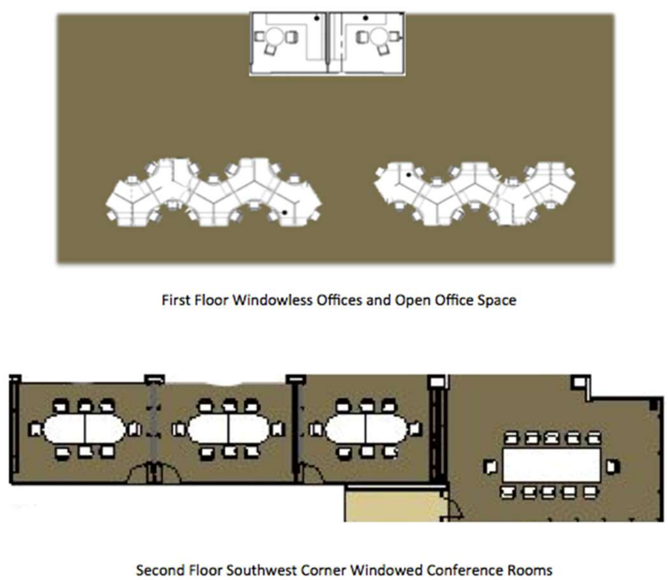


Figure 20. Opportunity to maximize worker benefits for Feature L01.

If this move had occurred prior to the tenant fit-out there would likely have been no additional costs to swap the conference rooms with the open office area. Based on the estimated productivity benefits of $5,535 per employee per year for each affected employee, the annual benefits for providing 29 workers access to windows and views and daylight/circadian lighting would be $160,509 per year. Table 13 shows a ten-year costs and benefits of both reaching the minimum feature requirements and maximizing the employee benefits relating to Feature L01.

Table 13. Ten-year costs and benefits of Feature L01 in MOS.

One-time costs required to achieve feature	Annual costs to maintain feature	Number of workers who can benefit from feature	Annual productivity benefits per employee	Annual productivity benefit total	Ten-year financial impact (Benefits minus costs)
Costs and benefits resulting from achieving minimum feature requirements					
$400 or less	$0.00	0	$5,534.79	$0.00	-$400.00
Costs and benefits resulting from maximizing Feature L01 benefits					
$400 or less	$0.00	29	$5,534.79	$160,508.91	$1,604,689.10

Unrelated to productivity, but important for a cost-benefit analysis for Feature L01, an article in the Electrical Power Research Institute (EPRI) Journal reported that office buildings with better daylighting designs can earn as much as 20% higher lease income when compared to buildings using only artificial light (Al-Ashwal & Hassan, 2018).

Feature L02 - Visual Lighting Design

This mandatory feature was created as an attempt to ensure appropriate light levels on work planes while considering types of tasks performed and average ages of building occupants. Table 14 shows the requirements of Feature L02 as well as the results of the MOS analysis.

Table 14. Requirements of Feature L02 and results of model analysis.

<table>
<tr><th>L02 Visual Lighting Design
(Precondition)</th><th colspan="4">Model Office Space Results</th></tr>
<tr><td>Part 1. Light levels for visual acuity</td><td>Legend</td><td>Model achieves feature with no changes necessary</td><td>Model achieves feature at little to no cost and effort</td><td>Model cannot achieve feature without considerable cost or effort</td></tr>
<tr><td>The following requirements are met:</td><td colspan="4" rowspan="6">When new, the project met the minimum illuminance recommendations of the IES Lighting Handbook 10th Edition for all indoor spaces. Outdoor lighting is outside the scope of this project. Due to lumen depreciation some areas are now delivering less than the minimum illuminance recommendations from general overhead lighting. When the space was new all areas met the minimum guidelines. There are several areas that exceed the illuminance recommendations when on at full power, but these areas have dimmable drivers and ballasts and advanced lighting controls and can be dimmed to meet illuminance guidelines at no additional cost and without any labor costs.</td></tr>
<tr><td>A. All indoor and outdoor spaces (including transition areas) comply with illuminance recommendations specified in one of the following lighting reference guidelines:</td></tr>
<tr><td>1. IES Lighting Handbook 10th Edition or IES Lighting Library.</td></tr>
<tr><td>2. EN 12464-1: 2011.</td></tr>
<tr><td>3. ISO 8995-1:2002(E) (CIE S 008/E:2001).</td></tr>
<tr><td>4. GB50034-2013</td></tr>
<tr><td>B. A lighting plan details the following:</td><td colspan="4" rowspan="4">A lighting plan took tasks into account and adjusted the light levels in the model office space accordingly. For instance, in the fabrication room where fine details are critical, the overhead lighting delivers 115-foot candles to the work surface. In offices where not as much light is necessary for typical office tasks the light levels are generally around 40-foot candles. The height of workstations was considered and programmed into the Revit Model. The lighting design took the age ranges for the majority of occupants into account. Most workers in this space range from mid 20s to Mid-40s.</td></tr>
<tr><td>1. Tasks or activities considered for visual lighting design in the project. All tasks and activities regularly undertaken by occupants are considered.</td></tr>
<tr><td>2. Height of work plane or other target of illumination.</td></tr>
<tr><td>3. Age ranges for the majority of occupants.</td></tr>
</table>

L02 Model Results Summary

The existing lighting and controls system met all requirements for Feature L02 when it was originally installed. Over the past eight years there has been significant lumen depreciation in two rooms and the general lighting no longer meets the minimum illuminance recommendations of the IES Lighting Handbook 10th Edition. There are some areas that exceed the IES recommendations, however based on the lighting and controls equipment installed it would have been possible to program scenes to meet the IES recommended ranges at no additional cost. Table 15 shows the IES recommendations for the most common areas in office buildings.

Table 15. IES Lighting Handbook 10th Edition light level recommendations for office spaces for occupants ages 25-65 (Energy Trust of Oregon, 2013).

Building Area & Task	Average Maintained Horizontal Foot-candles	Range of Maintained Horizontal Foot-candles	Notes
Private Office	40	30-50	Measured @30” Above Finished Floor
Open Office	40	30-50	Measured @30” Above Finished Floor
Conference Room	30	N/A	Matte surface reflectance of 40% recommended for the table
Restroom	18	7.5 - 30	N/A
Cafeteria/Break Room	15	5-20	N/A

Figure 21 shows a sample of the foot-candle measurements throughout the model office space.

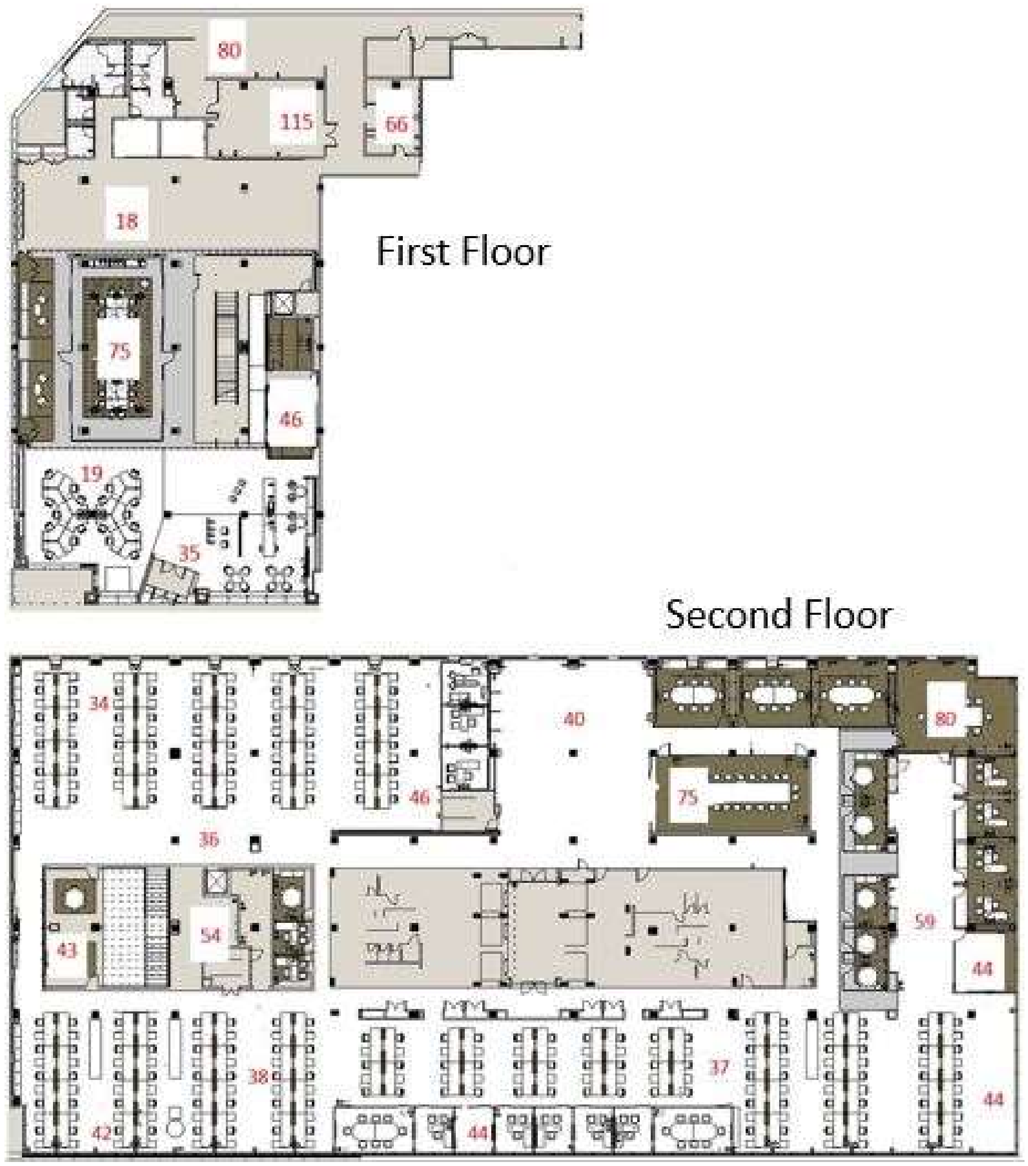


Figure 21. Typical light level readings taken throughout model office area.

While most spaces met or exceeded the IES Lighting Handbook 10th Edition illumination requirements Figure 22 highlights two areas in red that no longer meet the minimum light levels recommended by IES. Lighting calculations based off the installed fixture cut sheets showed the light levels in these areas was originally at least 34 foot-candles which would have met the IES guidelines at the time of installation.

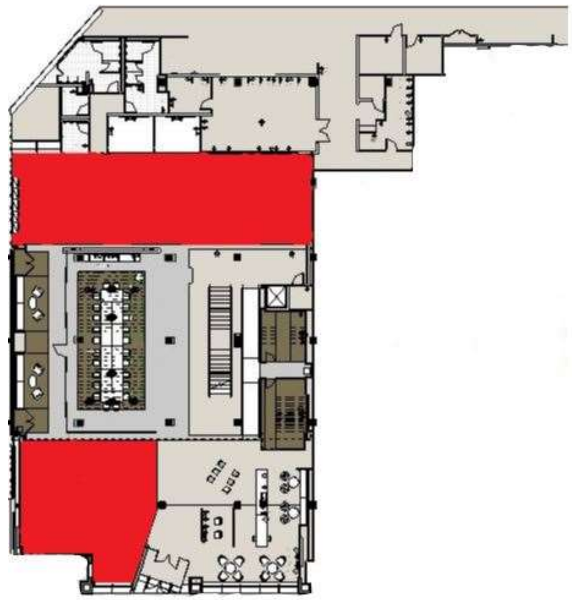


Figure 22. Workspace areas that no longer meet IES Lighting Handbook Tenth Edition illuminance guidelines due to lumen depreciation (areas in red).

Based on the results of this analysis the original MOS as designed and built would be able to meet Feature L02 at no cost and with no additional labor requirements. It is possible that a lighting designer may charge more to certify that each space complies with the IES Lighting Handbook 10th Edition guidelines but because this space meets the requirements of Feature L02 as designed, no additional charges were needed to meet this requirement for the MOS.

Illuminance levels can have a very large financial impact by boosting or lowering worker productivity. Table 16 shows the estimated value of increased productivity due to increasing luminance levels to improve visual acuity.

Table 16. Estimated Financial Benefits of lighting for visual acuity (Appendix 1).

Study	Productivity Increase Converted to Dollars	Reference
Hughes and McNelis	$7,312.50	(Halonen, Tetri, & Bhusal, 2010)
California Energy	$406.25	(CA Energy Commission, 2003)
Study of clerical workers 1	$4,062.50	(Hughes, 1978)
Study of clerical workers 2	$7,312.50	(Hughes, 1978)
Barnaby 1	$568.75	(Loftness & Hartkopf, 2003)
Barnaby 2	$1,625.00	(Loftness & Hartkopf, 2003)
AT Kearney	$3,656.25	(AT Kearney, 2015)
Hedge, 2016	$406.25	(Hedge, 2016)
Stenzel	$6,175.00	(Abdou, 1997)
Juslén Literature Review	$6,500.00	(Juslén & Tenner, 2005)
Gifford Meta-analysis	$0.00	(Clements-Croome, 2006)
National Lighting Bureau	$20,312.50	(Abdou, 1997)
National Lighting Bureau	$10,562.50	(Abdou, 1997)
Juslén 2007	$2,437.50	(Juslén, 2007)
Juslén, 2007	$6,256.25	(Juslén, 2007)
Juslén, 2007	$4,468.75	(Juslén, 2007)
Gligor	$0.00	(Gligor, 2004)
Bommel et al	$15,031.25	(Bommel et al., 2002)
Katzev	$0.00	(Katzev, 1992)
MacNaughton et al., 2017	$585.00	(MacNaughton et al., 2017)

Figure 23 shows the distribution of research results from Table 16. The results range from $0.00 to $20,312 with a median value of $3,859 and a mean value for productivity increases as a result of lighting for visual acuity of $4,998 per employee per year.

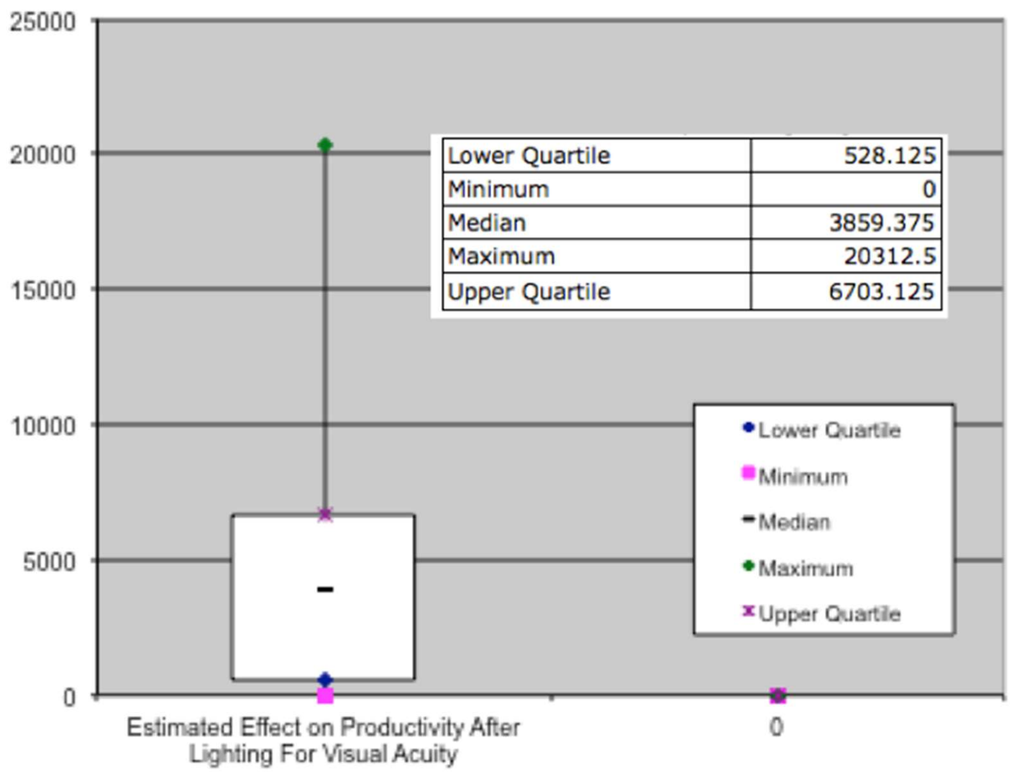


Figure 23. Distribution of estimated productivity increases after lighting for visual acuity.

Productivity increases as illuminance increases with older workers just as it does with younger workers (Boyce, 1973). However, as previously discussed, for older workers the illuminance levels must be considerably higher in order to reach similar levels of task efficiency as younger workers. Feature L02 addresses the higher lighting requirements by requiring projects to utilize illumination guidelines that recommend higher illuminance for older workers. If the higher levels recommended by the lighting guidelines in Feature L02 are implemented it is likely that many older workers will experience productivity benefits similar to those listed previously under lighting for visual acuity.

In addition to the quantitative analysis of the benefits of lighting for visual acuity, research used for this thesis revealed several qualitative benefits. Table 17 lists 21 studies that reported ancillary benefits not included in the quantitative analysis above.

Table 17. Ancillary benefits of lighting for visual acuity (for details see Appendix 1).

Study	Financial	Well-Being	Health	Safety	Cognitive Function	Performance	Reference
Carli, Giuli, & Zecchin						X X	(Carli, Giuli, & Zecchin, 2008)
Parsons			X X			X	(Parsons, 2000)
Smolders	X				X	X X X	(Smolders et al., 2012)
Weston						X	(Weston, 1922)
Weston and Taylor						X	(Weston & Taylor, 1925)
Baron et al.	X	XX			X	X X	(Baron et al, 1992)
Allen						X	(Katzev, 1992)
Gaetjens						X	(Katzev, 1992)
Irens						X	(Katzev, 1992)
Swale						X	(Katzev, 1992)
Stenzel						X	(Katzev, 1992)
Phipps-Nelson et al.		X			X	X	(Katzev, 1992)
Abdou						X	(Abdou, 1997)
Aries						XX	(Aries, 2005)
Sucov				X			(Abdou, 1997)
Shieh & Lin						X	(Shieh & Lin, 2000)
Bommel et al.				XX			(Bommel et al, 2002)
Chung & Lu			X			X	(Chung & Lu, 2003)
Juslén	X				XX	XXX	(Juslén, 2007)
Zakerian et al			XXX	X		X	(Zakerian et al, 2018)
UK Health and Safety Executive			X	X		X X	(Great Britain & Health and Safety Executive, 2002)
	3	3	7	5	5	27	

Figure 24 shows the distribution of the ancillary benefits listed in Table 17.

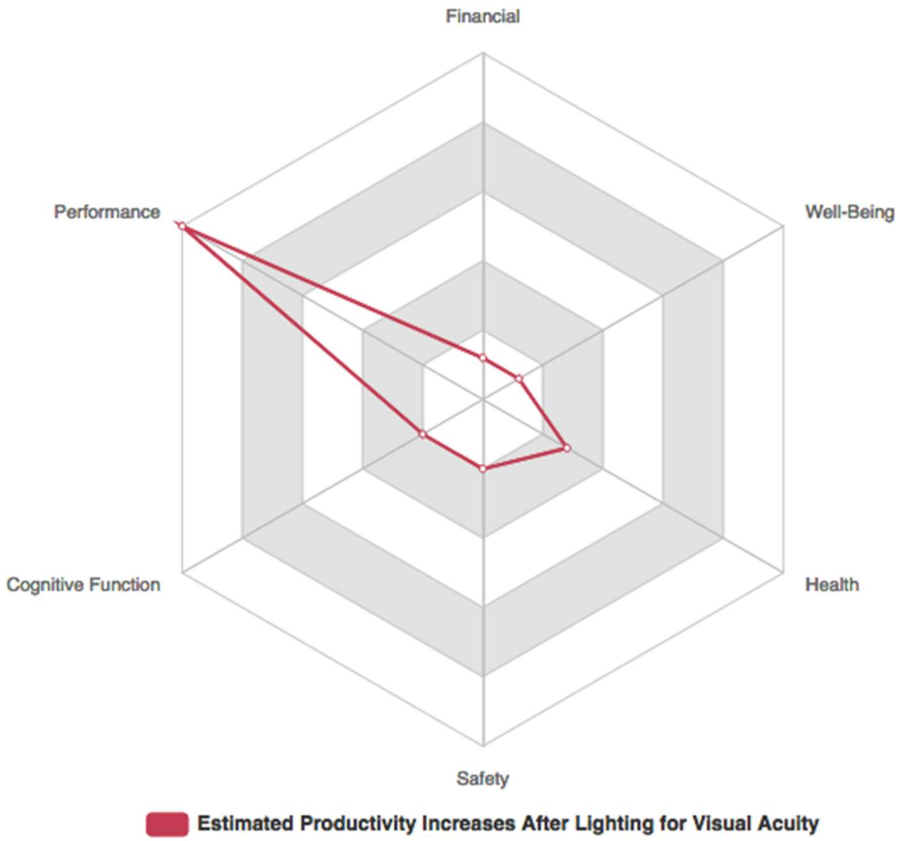


Figure 24. Qualitative benefits of lighting for visual acuity mentioned in scientific literature (Appendix 1).

Feature L02 Analysis of Results

It appears that there is strong evidence that increasing illumination in the workplace can lead to productivity improvements worth thousands of dollars per employee per year. However, most of the studies use a starting point of illumination that is higher than the requirements of some of the lighting guidelines that form the minimum illumination levels required by feature L02. Table 18 shows each study's initial foot-candle level as well as the higher foot-candle level tested for productivity improvements.

Table 18. Studies measuring productivity based on light level increases.

Study	Starting Light Level Converted to Foot Candles	New Light Level Converted to Foot Candles	Percent Improvement in productivity	Reference
Hughes and McNelis	46	139	9%	(Halonen et al., 2010)
CA Energy Commission	80	100	1%	(CA Energy Commission, 2003)
Study of clerical workers	50	100	5%	(Hughes & McNelis, 1978)
Study of clerical workers	50	150	9%	(Hughes & McNelis, 1978)
Barnaby 1	50	100	0.7%	(Loftness & Hartkopf, 2003)
Barnaby 2	50	150	2%	(Loftness & Hartkopf, 2003)
AT Kearney	Various	186	4.5%	(AT Kearney, 2015)
Hedge, 2016	28	79	1%	(Hedge, 2016)
Stenzel	32	93	7.6%	(Abdou, 1997)
Juslén Literature Review	23-37	93	8%	(Juslén & Tenner, 2005)
Gifford	6	182	0%	(Clements-Croome, 2006)
National Lighting Bureau	Poorly Illuminated	Higher	25%	(Abdou, 1997)
National Lighting Bureau	5	50	up to 13%	(Abdou, 1997)
Obayashi et al.	65	195	> 9%	Obayashi et al., 2007)
Juslen 2007	74	111	2.9% to 3.1%	(Juslen, 2007)
Juslén Night Shift Workers	74	111	7.7%	(Juslén, 2007)
Juslén, 2007	Various	Higher	5.5%	(Juslén, 2007)
Gligor	Various	Higher	0%	(Gligor, 2004)
Bommel et al	9	93	7% to 30%	(Bommel et al., 2002)
Bommel et al	9	371	30%	(Bommel et al., 2002)
Katzev	Various	Various	0%	(Katzev, 1992)
MacNaughton et al., 2017	Various	20 foot-candles higher	0.72%	(MacNaughton et al., 2017)

A simple linear regression was calculated to predict productivity increases based on illuminance levels. A significant regression equation was found (F(1,12) = 35.32, P<0.000, with a multiple R^2 of 0.75. Predicted worker productivity increases are equal to 5.57234 + 0.06532 (light level) when productivity increases are measured as a percentage and light levels are measured in foot-candles. As light levels increase, worker productivity improves 0.065% for each additional foot-candle. Figure 25 shows diagnostic plots summarizing the results of the linear regression.

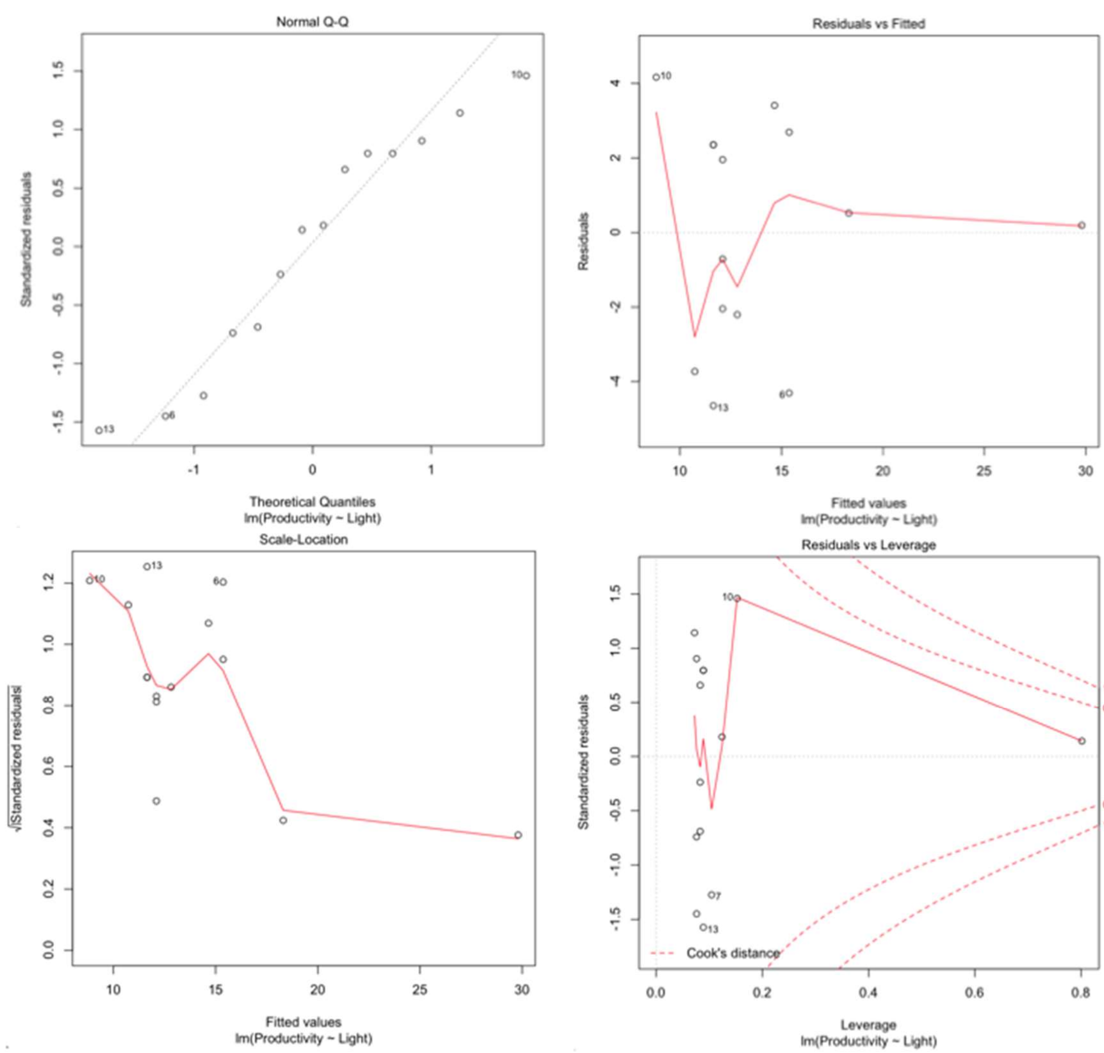


Figure 25. Diagnostic plot results from linear regression analysis.

Figure 26 provides additional details from the linear regression and shows the coefficients and p-value showing the regression is statistically significant.

```
Residuals:
    Min      1Q  Median      3Q     Max
-4.6468 -2.1628  0.3581  2.3532  4.1618

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  5.57234    1.65368   3.370  0.00557 **
Light        0.06532    0.01099   5.943 6.78e-05 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 3.096 on 12 degrees of freedom
Multiple R-squared:  0.7464,  Adjusted R-squared:  0.7253
F-statistic: 35.32 on 1 and 12 DF,  p-value: 6.783e-05
```

Figure 26. Regression output with coefficients.

For the linear regression, only studies that listed an initial and final light level were included. The Gifford study was eliminated from the analysis because it was an outlier as it was the only study that reported initial light levels and higher light levels that didn’t show any improvement in productivity. One of two Bommel studies was eliminated from the analysis because it was the only study using night shift workers and the large increase in productivity would have skewed the results. In order to standardize the data, each study’s illuminance levels were broken into 10 foot-candle increments starting at 10 foot-candles and the productivity results reported by each study were divided among each 10 foot-candle increment between the initial light level and the final light level. Each study that reported illuminance levels that fit into a specific 10 foot-candle range was averaged together to determine a mean productivity value for each ten foot-candle increment. When a study reported results where the starting illuminance level was higher than other studies that reported productivity increases, the average productivity increase for each ten foot-candle increment below the initial light level of each study was added to the higher value in order to standardize samples for the linear regression. The results show that when initial light levels are lower, productivity increases quickly as illumination increases. As the illuminance levels rise there are additional productivity increases but they increase more slowly. Table 19 shows predicted incremental productivity increases at various light levels.

Table 19. Productivity increases at various foot-candle increments.

Increasing illumination levels	**Predicted productivity**
From 10 to 50 foot-candles	9.06% increase
From 50 to 100 foot-candles	3.79% increase
From 100 to 150 foot-candles	3.42% increase
From 150 to 200 foot-candles	3.18% increase

The MOS automatically met the requirements of this feature without any changes necessary and as a result there would be no additional costs to implement Feature L02. There would also be no additional benefits that could be attributed to upgrading the model space to achieve Feature L02. There are currently two areas previously shown in Figure 22 where the general illumination has fallen below IES Lighting Handbook 10th Edition guidelines. The first floor northeast open office averages 19 foot-candles and the first floor southern open office area averages 18 foot-candles. Using the equation from the multiple regression analysis (5.57234 + 0.06532 (light level) and using 18 foot candles as the initial light level and increasing the light level to 50 foot-candles (the high end of the IES illuminance recommendations for office work planes (Energy Trust of Oregon, 2013) the predicted increase in productivity would be 2.09% per employee per year. Using the average U.S. office worker salary of $81,500 yields an increase of $1,703 per person affected by the higher illuminance each year. The first floor southern open office area has 27 workers and no windows. The first floor northeast open office area has 18 workers and north facing windows. For the southern open office area, the estimated productivity increases from raising the illumination is predicted to be $45,990 per year. For the northern open office area, the measured foot-candle level at the time of site inspection was 19 foot-candles. However, according to the $sDA_{300,50}$ analysis approximately 50% of the northeastern open office area receives 27.87 foot-candles or higher for at least half of the workday. Figure 25 is a Light Stanza model of the $sDA_{300, 50\%}$ for the northern open office areas showing the areas that typically receive natural daylight. For this analysis it will be assumed that only half (nine) of the workers in the northeastern open office area would benefit from increased illumination, leading to a predicted productivity improvement of $15,330 per year.

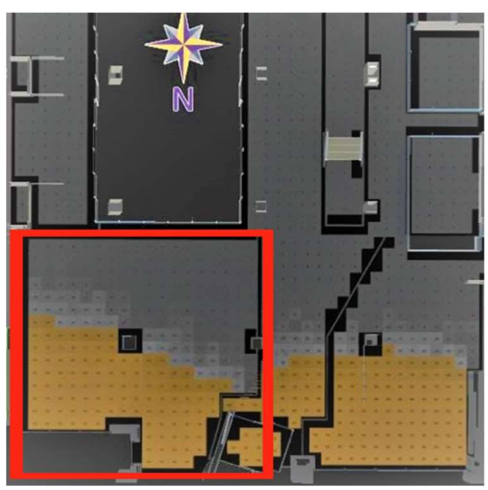


Figure 27. Light Stanza $sDA_{300,50\%}$ showing approximately half of the northern open office area (highlighted in red) receives substantial daylight.

Table 20 shows the ten-year costs and benefits for both meeting the minimum feature requirements and maximizing feature benefits.

Table 20. Ten-year costs and benefits of both meeting the minimum requirements of Feature L02 and maximizing the feature benefits.

One-time costs required to achieve feature	Annual costs to maintain feature	Number of workers who can benefit from feature	Annual productivity benefits per employee	Annual productivity benefit total	Ten-year financial impact (Benefits minus costs)
Costs and benefits resulting from achieving minimum feature requirements					
$0.00	$0.00	0	$4,997.78	$0.00	$0.00
Costs and benefits resulting from maximizing benefits of Feature L02					
$0.00	$0.00	36	$1,703.35	$61,320.60	$613,206

Because the MOS originally met the requirements of Feature L02 there are no costs or benefits associated with meeting the minimum feature requirements. In order to maximize the benefits of the feature, Table 20 shows the benefits predicted if the MOS used lighting that maintained 50 foot-candles over a ten-year period.

Feature L03 – Circadian Lighting Design

The purpose of this optional feature is to provide workers with appropriate exposure to light in order to encourage circadian entrainment. Table 21 shows the requirements of Feature L03 as well as the results of the MOS analysis.

Table 21. Requirements of Feature L03 and results of model analysis.

L03 Circadian Lighting Design (Max 3 points)			
Part 1. Lighting for the circadian system			
Electric lighting is used to achieve light levels shown in the table below as measured on the vertical plane at eye level of the occupant. The light levels are achieved at least between the hours of 9 a.m. and 1 p.m. and may be lowered after 8 p.m. at night:			
The project meets the following requirements in regularly occupied spaces:			
Legend	Model achieves feature with no changes necessary	Model achieves feature at little to no cost and effort	Model cannot achieve feature without considerable cost or effort
Option 1	**Or**	**Option 2**	**Model office space results**
At least 150 EML [136 melanopic equivalent daylight D65]	1 Point	The project achieves at least 120 EML [109 Melanopic equivalent daylight D65] with electric light and at least 2 points in Feature L05: Enhanced Daylight Access.	Project does earn at least 2 points in Feature L05. Most spaces exceed 120 EML however two rooms do not currently meet the minimum EML for L03. After examining fixture cut sheets and performing lighting calculations it was determined that all regularly occupied spaces achieved at least 120 EML when first installed. After 8 years of lumen depreciation two rooms no longer meet the requirement.
At least 240 EML [218 melanopic equivalent daylight D65]	3 points	The project achieves at least 180 EML [163 melanopic equivalent daylight D65] with electric light and at least 2 points in Feature L05: Enhanced Daylight Access.	Most of the office space currently exceeds 180 EML. Only two areas are currently below 180 EML; The two first floor open offices are currently at 114 EML. However, because the entire MOS originally achieved over 180 EML the model office space would have achieved this feature at no additional cost.

Feature L03 Model Results Summary

The MOS automatically achieved all three points for Feature L03.

Because the project earned two out of three points for Feature L05 it was able to achieve three points for Part 1 Option 2 by achieving at least 180 Equivalent Melanopic Lux (EML) in regularly occupied spaces. The WBSv2 allows two options for light rating/measurement systems in order to determine eligibility for Feature L03. Similar to EML, the Equivalent Daylight (D65) rating system, enables calculations and conversions of measured quantities related to the non-visual effects of light (International Commission on Illumination, 2019). It was based on the international standard CIE S 026/E:2018. For this thesis EML was used to determine the model's eligibility for Feature L03.

EML is a metric used to measure the biological effects of light on humans based on light intensity and spectral power density (WELL Certified, 2018b). Within a spectrum of light, each equivalent α-opic lux is related to each other by the Melanopic Ratio constant (R) (WELL Certified, 2018a). EML is calculated by multiplying the measured photopic lux (L) by (R): $EML = L \times R$. (WELL Certified, 2018a). The color temperature of all lighting in regularly occupied areas of the model office building is 3,000 Degrees Kelvin (K) and most lighting sources are LED. In order to determine the EML for each regularly occupied area, the melanopic ratio (R) of 0.59 was calculated based on Table L.1 of the WBS (IWBI, 2017). With an R of 0.59 the minimum measured lux must be at least 306, or 28.4 foot-candles. Figure 28 shows the foot-candle measurements throughout the building. The areas in red are areas that no longer meet the requirements of L03 and the area in yellow is likely to drop below 180 EML within a few years due to lumen depreciation.

Figure 28. Foot-candle readings showing areas in red that no longer meet feature L03. Area in yellow is likely to fall under 180 EML within a few years due to lumen depreciation.

Circadian lighting and the related benefits have already been discussed during the analysis of Feature L01. The primary difference between Feature L03 and Feature L01 is that for Feature L01 only 30% of workstations need to be near windows in order to achieve the feature. To achieve Feature L03 the project must meet minimum EML or CS requirements at all workstations, which would ensure benefits to the other 70% of the building occupants.

The mean value of circadian lighting productivity estimates discussed under Feature L01 is $5,469. Because the MOS met the lighting recommendations of the IES Handbook 10th Edition by using 3000 K LED fixtures when it first opened, there would have been no additional costs required to achieve Feature L03. Because the original design achieved all three points of this feature the MOS would have already received all the benefits as well.

Feature L03 Analysis of Results

There are two areas in the MOS that no longer meet the requirements of Feature L03. These areas are the first floor northeastern open office area with 18 workers and the first floor southern open office area with 27 workers. These are the two areas that also no longer meet the minimum illumination requirements for Feature L02. By raising the illumination level of these two areas to meet Feature L03 it would automatically re-enable the model office space to meet Feature L02 and vice versa due to the original specification of 3000 K LED fixtures. Because both Feature L02 and L03 can be achieved by replacing the now dim LED fixtures, the costs would be the same and both features would be achieved again.

In order to estimate the incremental productivity improvements above what has been predicted from increasing the illumination to 50 foot-candles, the values from Feature L02 will be subtracted from the predicted value of daylight and circadian lighting. The per worker per year value of daylight and/or circadian lighting is estimated to be $5,569 and the estimated value of increasing the illumination levels for Feature L02 is $2,364 with a difference of $3,205. The main difference between Features L02 and L03 in terms of potential productivity increases is whether the light is capable of leading to circadian entrainment. The illumination level is an essential component of circadian lighting but the spectral power distribution can be just as important. The difference in the estimated values of each feature is presumably the additional value of biologically active light affecting circadian entrainment. For the cost-benefit analysis, the same assumptions used for Feature L02 regarding the portion of workers exposed to daylight will be used for this analysis.

Table 22 shows the ten-year costs and benefits of implementing Feature L03. It is important not to double count the benefits (with Feature L02) when calculating the overall impact the WBSv2 would have on this building.

Table 22. Ten-year costs and benefits of restoring lighting back to original requirements of Feature L03.

One-time costs required to achieve feature	Annual costs to maintain feature	Number of workers who can benefit from feature	Annual productivity benefits per employee	Annual productivity benefit total	Ten-year financial impact (Benefits minus costs)
$0.00	$0.00	36	$5,568.90	$200,480.40	$2,004,804.00

Feature L04 - Glare Control

The purpose of this optional feature is to minimize brightness-contrasts and glare that can lead to reduced occupant comfort, health problems and decreased performance. Table 23 shows the requirements of Feature L04 as well as the results of the MOS analysis.

Table 23. Requirements of Feature L04 and results of model analysis.

WSBv2 Feature	Model Office Space Results		
L04 Glare Control (max 3 points)			
Part 1. Control Solar Glare (Two points) - Choose between the following:			
Option 1. Window shading - The following requirements are met:			
Legend	Model achieves feature with no changes necessary	Model achieves feature at little to no cost and effort	Model cannot achieve feature without considerable cost or effort
A. All exterior envelope glazing has shading. Atria or lobbies may be excluded.	Model project meets this feature. All windows have blinds or shades.		
B. The shading is controllable by the occupants or set to automatically prevent glare. If occupants control shading, all shades are raised or retracted either manually or automatically at least twice per week.	Model meets this requirement as all shades are manually controllable and can be moved as often as necessary.		
Option 2. Glare calculation: The following requirement is met:			
Annual sunlight exposure of $ASE_{1000,250}$ is achieved for no more than 10% of regularly occupied space.	Project meets this requirement. Daylight analysis shows that $ASE_{1000, 250}$ is exceeded in only 4% of regularly occupied space.		
Part 2. Manage glare from electric lighting (2 points)			
Each luminaire meets one of the following requirements for regularly occupied spaces. Wall wash fixtures properly aimed at walls, as specified by manufacturer's data, as well as decorative fixtures may be excluded from meeting these requirements: **A.** 100% of light is emitted above the horizontal plane. **B.** Unified Glare Rating (UGR) values are met as per the below conditions: **1.** Luminaires installed at a height of 16 feet or lower meet UGR of 19 or lower. **2.** Luminaires installed at a height greater than 16 feet meet UGR of 22 or lower.	The project does not meet this feature as designed due to fixtures in the fabrication room with high UGR Values. There are several high UGR Value wall washers that would be exempt if properly aimed at the walls but in some cases the wall washers are aimed at other points in the room. This could be corrected simply by turning them. All other fixtures meet at least one of the four requirements for Part 2.		

C. Shielding angles are as described in the below table:

Luminance	Shielding angle, α (α = 90 - cutoff angle)
< 20,000 cd/m² (including reflected sources)	No shielding required
20,000 cd/m² to 50,000 cd/m²	15°
50,000 cd/m² to 500,000 cd/m²	20°
> 500,000 cd/m²	30°

D. Fixtures have a luminance of less than 10,000 cd/m2 between 45 and 90 degrees from nadir, and/or an intensity of less than 1,000 candela between 45 and 90 degrees from nadir.

Feature L04 Model Results Summary

The MOS automatically earned two points for Part 1 by meeting the requirements for both Options 1 and 2. There are aluminum mini-blinds on all windows on the second floor and the model has automated shades installed on the first floor. For Part 1, Option 2, a glare analysis was conducted using Autodesk Revit 2019 with the Revit Insight Plugin. Figure 29 shows that only 4% of the model office space exceeded $ASE_{1000, 250}$ (areas in red). The model did not earn any points for Part 2 due to fixtures in the fabrication room having high Unified Glare Ratings (UGR) and improperly aimed wall washers causing glare conditions.

Figure 29. Daylight glare analysis showing $ASE_{1000,250}$ is exceeded in only 4% of regularly occupied space (areas in red).

Because the MOS has shading devices on all windows, there are no additional costs required to achieve L04 Option 1. A field study of office buildings showed that 93% of workspaces had some form of interior window controls for shading (Heschong, 2015) which means that meeting part one of this feature would not affect the upfront material costs on the majority of projects. The daylight analysis allowed the model to meet L04 Option 2 at no additional cost.

For the MOS to achieve L04 Part 2 the lighting in the fabrication room will need to be replaced. To determine the cost to upgrade the lighting in the fabrication room to meet the requirements of L04 a medium grade, similar style fixture was selected that is capable of delivering the same light levels (115-foot candles) as the currently installed fixtures without exceeding a UGR of 19.

A lighting manufacturer's representative performed the lighting calculations to ensure an appropriate fixture was selected and a quote was obtained. Because the focus of this thesis is to determine the cost delta of upgrading a building to meet the features of

WBSv2 prior to construction, an estimate of the price of the original lighting in the fabrication room was deducted from the price of the new lighting. Additionally, labor costs were not estimated because installing a low UGR fixture would cost the same as installing a high UGR fixture. The price delta between the original lighting fixtures and the new fixture upgrade was determined to be $12,240. For the wall washers, all that needs to be done to bring them into compliance is to properly aim them toward the wall. This could be done at no additional cost.

Figure 30 shows the high UGR lighting in the fabrication room (exposed T-5 LED Tubes) that must be replaced in order to achieve Part two of Feature L04. The proposed replacement delivers at least 115 foot-candles to the work surfaces with a UGR below 19.

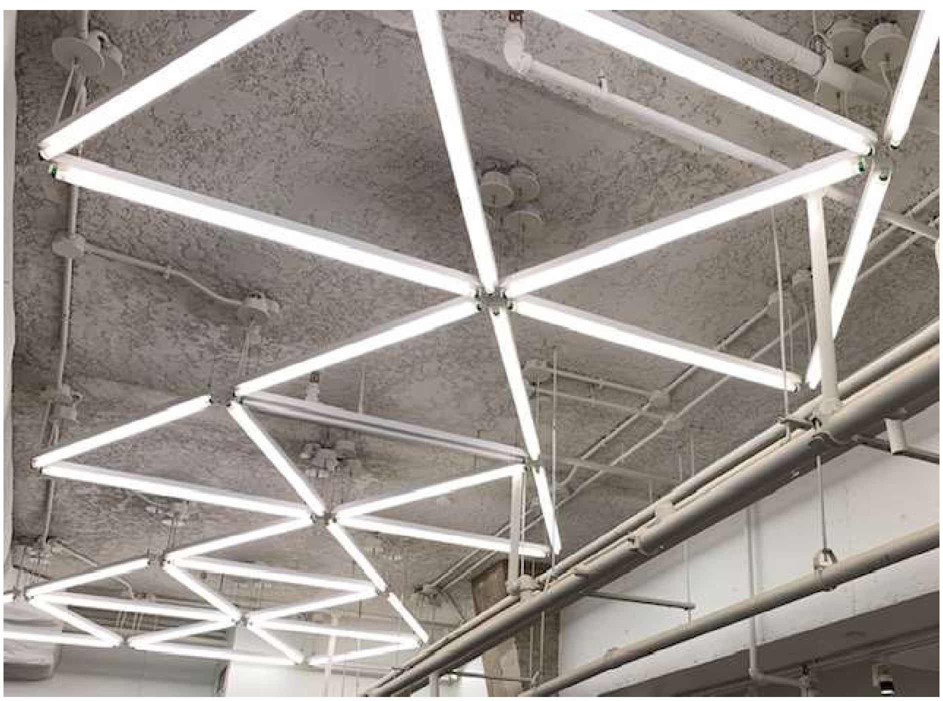


Figure 30. Photograph of the fixtures that would have prevented the MOS from achieving Part two of Feature L04 due to a high UGR.

Table 24 shows the results of three studies showing the impact of solar glare on employees. The results only apply to employees near windows during periods of glare. The Zhang and Alton study only reported costs of absenteeism caused by glare and as a result will not be included in the average productivity estimate. The mean value of controlling solar glare is $769 per affected employee.

Table 24. Productivity benefits related to controlling solar glare for affected employees.

Study	Productivity Increase Converted to Dollars	Reference
Heschong Call Center Study	$914.06 for each affected employee	California Energy Commission & Heschong, 2003).
Wymelenberg	$624.60 for each affected employee	(Wymelenberg, 2013)
Zhang and Alton	$187.00	(Zhang & Alton, 2010)

Table 25 shows results of studies reporting productivity improvements from reducing glare from electric light sources. The mean value of increased worker productivity is $4,814. The large difference between the financial impact of solar glare and glare from electric light is likely due to the fact that the movement of the sun ensures that most workers are only impacted for a small portion of the work day, whereas glare from electric light sources can cause discomfort all day, every day.

Table 25. Productivity benefits of reducing glare from electric light sources.

Study	Productivity Increase Converted to Dollars	Reference
Hedge et al.	$2,437.50	(Loftness & Hartkopf, 2003)
Allen	$10,725.00	(Abdou, 1997)
Reno Post Office	$4,875.00	(Loftness & Hartkopf, 2003)
1992 IEEE Industry Applications Society Annual Meeting	$1,218.75	(CA Energy Commission, 2003)

In addition to the quantitative analysis of the benefits of controlling glare, the research used for this thesis reported several qualitative ancillary benefits. Table 26 shows five studies referenced in this thesis that listed the following ancillary benefits that were not included in the quantitative analysis above.

Table 26. Ancillary Benefits of Controlling Solar Glare

Study	Financial	Well-Being	Health	Safety	Cognitive Function	Performance	Reference
Linney	X	XXX	XX		XX	XXXXX	(Linney, 2008)
Brotas and Wienold	X			X		X	(Brotas & Wienold, 2014)
Bommel et al.				X			(Bommel et al., 2002)
Zhang & Alton		X				X	(Zhang & Alton, 2010)
(Juslén & Tenner, 2005)		X				XXXXX	(Juslén & Tenner, 2005)
Totals	2	5	2	2	2	12	

Table 27 shows four studies that reported the ancillary benefits by limiting glare from electric light sources. Figure 31 shows the distribution of these benefits.

Table 27. Ancillary benefits of controlling glare from electric light.

Study	Financial	Well-Being	Health	Safety	Cognitive Function	Performance	Reference
Abdou	X	X				X	(Abdou, 1997)
Sundstrom	X					X	(Sundstrom and Sundstrom, 1986)
Bommel et al.				X			(Bommel et al., 2002)
(Juslén & Tenner, 2005)		X				XXXXX	(Juslén & Tenner, 2005)
Totals	2	2	0	1	0	7	

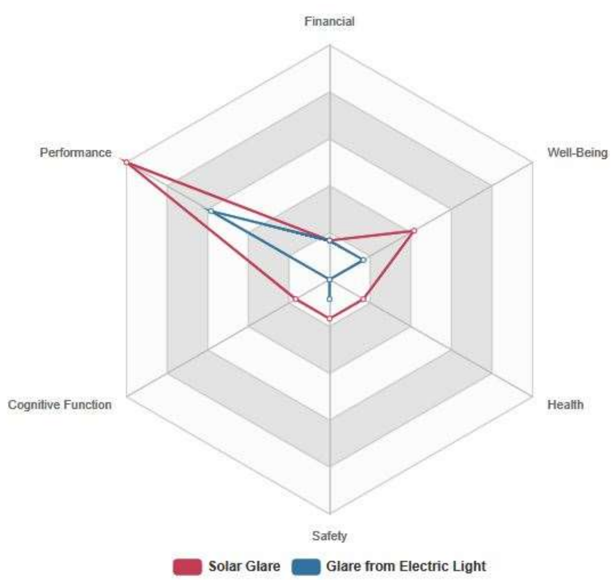


Figure 31. Distribution of ancillary benefits reported for reducing solar glare and glare from electric lights (Appendix 1).

Feature L04 Analysis of Results

The model office area automatically achieved Feature L04 Part 1, Option 1 as designed and built. Therefore, there are no additional costs necessary to achieve this option. There are also no additional benefits as a consequence of this feature. There is a potential that if the manual shades were more actively controlled additional benefits could be achieved. The daylight and glare analysis (ASE $_{1000,\,250}$) discussed previously, showed that 4% of the model area was impacted by high levels of solar glare for more than 250 hours per year. It will be assumed that 4% of employees were affected by solar glare for 250 hours per year or 12.5% of the year. That applied to nine employees. Feature L04 requires that manual shades be somewhat actively controlled. Using the mean value of the estimated productivity increases due to controlling solar glare ($4,814) multiplied by 12.5% of the work year yields $602 per employee affected by glare. In the model office space approximately nine workers would be exposed to glare costing $5,416 in lost productivity per year. If actively controlled manual shades reduced glare an additional 25%, it could provide an increase in productivity of $1,354 per year. Automated shades could virtually eliminate the negative effects of solar glare, however there would be a significant up-front cost to retrofit the space.

Electric Glare

As previously discussed for the model office space to achieve Part 2 of Feature L04 a fixture change is required. The cost to upgrade the fixtures in the fabrication room would be $12,240. This would affect approximately 13 workers who are constantly exposed to glare from these fixtures while sitting at their workstations and facing forward. Using the mean value of $4,814 for increased productivity from reducing glare from electric lights multiplied by 13 employees would yield $62,583. Table 28 shows the total ten-year costs and benefits of upgrading the original design of the model office to meet feature L04.

Table 28. Ten-Year costs and benefits of implementing Feature L04.

One-time costs required to achieve feature	Annual costs to maintain feature	Number of workers who can benefit from feature	Annual productivity benefits per employee	Annual productivity benefit total	Ten-year financial impact (Benefits minus costs)
Controlling Solar Glare – Minimum Feature Requirements					
$0.00	$0.00	0	$601.75	$0.00	$0.00
Controlling Solar Glare – Maximizing Feature Benefits (Adjusting shades more frequently than required by Feature L04)					
$0.00	$0.00	9	601.75 X 25% = $150.44	$1,354.00	$13,539.38
Achieving Feature L04 Part 2 (Replacing fabrication room fixtures)					
12,240.00	$0.00	13	$4,814.06	$62,582.78	$613,587.80

Feature L05 – Enhanced Daylight Access

The goal of this optional feature is to require projects to design spaces to integrate daylight into indoor environments so daylight may be used for visual tasks along with electric lighting. It also provides individuals with a connection to outdoor spaces through view windows. This feature is similar to mandatory precondition Feature L01. This feature ensures that there are more building occupants getting access to higher levels of daylight and better views. Table 29 shows the requirements of Feature L05 as well as the results of the MOS analysis.

Table 29. Requirements of Feature L05 and results of model analysis.

<table>
<tr><th colspan="2">WSBv2 Feature</th><th colspan="2">Model Office Space Results</th></tr>
<tr><td colspan="4">L05 Enhanced daylight access (Max 3 points)
Part 1. Implement enhanced daylight plan (1 point)</td></tr>
<tr><td>Legend</td><td>Model achieves feature with no changes necessary</td><td>Model achieves feature at little to no cost and effort</td><td>Model cannot achieve feature without considerable cost or effort</td></tr>
<tr><td colspan="2">A. 70% of all workstations are within 25 feet of transparent envelope glazing or atria. Visible light transmittance (VLT) of transparent glazing is greater than 40%.</td><td colspan="2">Project meets this feature. Approximately 80% of workstations are within 25' of a window with a VLT of 85%.</td></tr>
<tr><td colspan="2">B. Window area is no less than 10% of the regularly occupied floor area. VLT of transparent glazing is greater than 40%.</td><td colspan="2">Project meets this feature. Total window area for both floors is 5,112 square feet and total floor area is 45,349 square feet. Window area is 11.2% of entire floor area.</td></tr>
<tr><td colspan="4">Part 2. Implement advanced daylight simulation (max 2 points) - The following requirement is met:</td></tr>
<tr><td colspan="4">A. Projects demonstrate through computer simulations that sDA 300,50% is achieved for the area on each floor as shown in the table below:</td></tr>
<tr><td>sDA 300,50%</td><td>Points</td><td colspan="2">Results</td></tr>
<tr><td>Achieved for > 55% of regularly occupied floor area</td><td>1</td><td colspan="2">Project does not achieve this feature. Project meets $sDA_{300,50\%}$ for only 41% of total floor space.</td></tr>
<tr><td>Achieved for > 75% of regularly occupied floor area</td><td>2</td><td colspan="2">Project does not achieve this feature. Project meets $sDA_{300,50}$% for only 41% of total floor space.</td></tr>
<tr><td colspan="4">Part 3. Ensure views (1 point)</td></tr>
<tr><td colspan="4">Transparent envelope glazing provides access to views for at least 50% of regular building occupants. Views meet at least two of the following requirements:</td></tr>
<tr><td colspan="2">A. If at ground floor, distance from fenestration to roadway is at least 25 feet from the exterior of the glazing.</td><td colspan="2">The roadway on the first floor is 27’ 6” from window.</td></tr>
<tr><td colspan="2">B. View factor of 3 or greater</td><td colspan="2">Approximately 79% of building occupants have a view factor of 3 or greater.</td></tr>
<tr><td colspan="2">C. Views with a vertical view angle of at least 30 degrees from occupant facing forward or sideways provide a direct line of sight to the ground or sky.</td><td colspan="2">More than 50% of building occupants have a direct line of sight to the sky or ground.</td></tr>
</table>

Feature L05 Model Results Summary

The MOS automatically achieved two out of three points for this feature. The model achieved L05 Part 1A by having approximately 80% of workstations within 25' of a window with a VLT of 85%. The MOS also achieved Part 1B with a window area of 11.2% of entire floor area. The model did not earn any points for L05 Part 2 because the area of the model that achieved an $sDA_{300,50\%}$ was too low to meet either option. In order to achieve points for Part 2, it would require changes to the building envelope and therefore Part 2 will not be considered as an option to upgrade. The MOS earned a point for all three view options (at least two were required) with more than 79% of building occupants having a view factor of three or higher. Figure 32 illustrates the various view factors referenced in Feature L05.

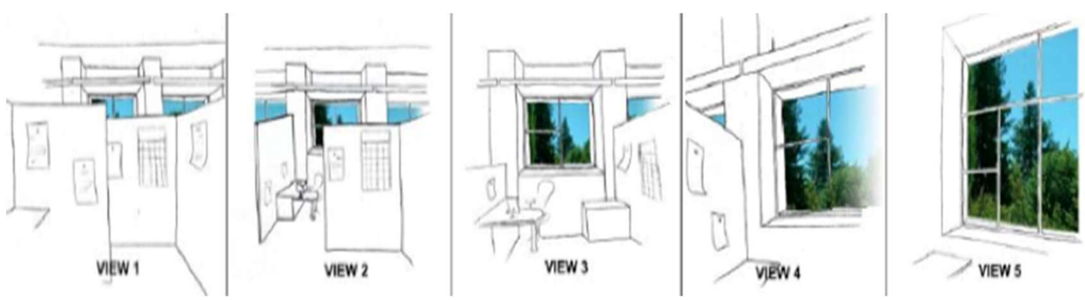


Figure 32. Illustration of view factors referenced in the WBSv2 Feature L05 (California Energy Commission, 2003).

Figure 33 was photographed from the open office area on the second floor showing the views that are typical for most of the second floor.

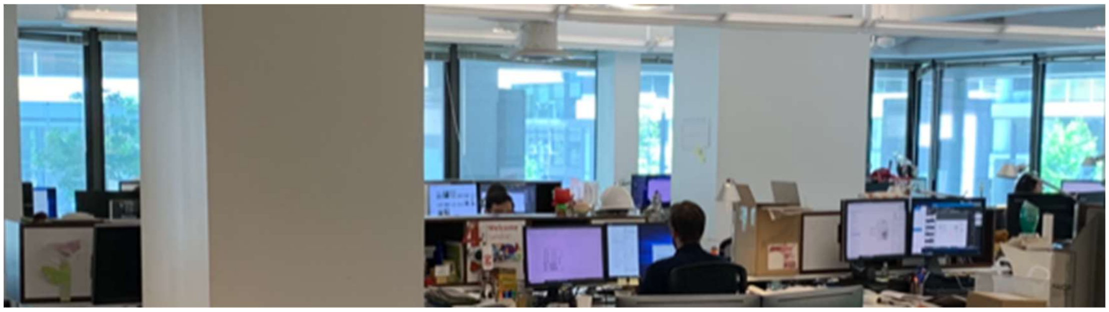


Figure 33. Typical views for majority of occupants in MOS. June, 2019.

To illustrate the views further from the windows while protecting the privacy of workers in the MOS, a rendering of the interior open office space was created and is shown in Figure 34.

Figure 34. Rendering of model office space highlighting window space and view ratings.

The model office space automatically achieved two out of three points for Feature L05. The third point is not available, as it would require changing the building envelope.

There are no points available for upgrading and therefore there are no incremental costs required for achieving this feature.

Similar to Feature L01, Feature L05 focuses on increasing the number of building occupants exposed to daylight and views in the workplace. These benefits have already been covered in the background section under Feature L01.

The model space was designed in such a way that it already achieved all the requirements of Feature L05 that it could without altering the building envelope. As such, there are no incremental costs but there are also no incremental benefits that can be attributed toward this feature as they were already maximized under Feature L01. As discussed previously the mean value of research estimates for productivity increases from workers with daylight and views is $5,535 for each employee each year.

Feature L05 Analysis of Results

Features L01 and L05 are similar as the goal of each feature is to give building occupants access to daylight and views. Feature L01 is a mandatory feature and as such it cannot set too high a requirement on the number of employees with access to daylight and views because that may disqualify many potential WBS projects from seeking certification. Feature L05 rewards projects that are designed to give additional building occupants access to daylight and views above and beyond the minimum requirements of Feature L02. Table 30 shows that if Feature L01 had not already provided daylight and views to all workers, the benefits for each worker moving from a windowless workstation to a workstation with windows would be worth an average of $5,5345 per employee per year. For the MOS there were no costs and no benefits available, as the project had already achieved this feature with its original design.

Table 30. Ten-Year costs and benefits of implementing Feature L05.

One-time costs required to achieve feature	Annual costs to maintain feature	Number of workers who can benefit from feature	Annual productivity benefits per employee	Annual productivity benefit total	Ten-year financial impact (Benefits minus costs)
$0.00	$0.00	$0.00	$5,534.79	$0.00	$0.00

Feature L06 – Visual Balance

This optional feature requires projects to implement strategies that consider reducing eyestrain due to high luminance ratios and to create a visually comfortable lighting environment. Table 31 shows the requirements of Feature L06 as well as the results of the MOS analysis.

Table 31. Requirements of Feature L06 and results of model analysis

<table>
<tr><th>WSBv2 Feature</th><th colspan="2">Model Office Space Results</th></tr>
<tr><td colspan="3">L06 Visual Balance - Part 1. Manage brightness (1 point)</td></tr>
<tr><td colspan="3">At least four of the following requirements are met in all regularly occupied spaces:</td></tr>
<tr><td>Legend - Model achieves feature with no changes necessary</td><td>Model achieves feature at little to no cost and effort</td><td>Model cannot achieve feature without considerable cost or effort</td></tr>
</table>

A. Main rooms do not exhibit 10 times greater or lesser luminance than an ancillary space. This is to avoid substantial changes in light levels as occupants move from one space to another.	There were no instances where main rooms exhibited 10 times greater or lesser luminance than ancillary spaces. The largest difference in this building was the 1st floor fabrication room (115 foot-candles) exhibits 6.39 times the illuminance of the 1st floor southern open office area (18 foot-candles).
B. Surfaces do not exhibit 3 times greater or lesser luminance than an adjacent surface. This is to avoid substantial changes in light levels as occupants look around their immediate area.	There are several instances where surfaces exhibit luminance greater than 3 times that of an adjacent surface. Much of this could be corrected by dimming specific luminaires. The fixtures are digitally addressable in most cases so adjusting an individual fixture to manage luminance ratios is possible.
C. Surfaces do not exhibit 10 times greater or lesser luminance than another remote surface in the same room. This is to avoid substantial changes in light levels as occupants look around the room.	Out of more than three dozen illuminance measurements there were no instances of surfaces exhibiting 10 times greater or lesser luminance in the same room.
D. Changes in light levels to 1.5 times higher or lower than initial light levels are carried out over the span of at least 30 minutes in steps or with a smooth transition. Timing considerations in the rate of change of light levels or spectrum diminish abrupt or disruptive lighting transitions.	The dimmable lighting in this office space is controlled by a Lutron Quantum lighting control system that is capable of a slow fade from one light level to another over the course of 30 minutes or longer. This has not been programmed to happen at this facility but it could be implemented at no cost with little time or effort required.
E. Uniformity of at least 0.4 is achieved on work planes. Exclude supplemental lighting from calculations	The uniformity of most work planes is higher than .7. The lowest uniformity tested during the site visit was .55.
F. One section of the ceiling does not exhibit 10 times greater or lesser luminance than another section of the ceiling in the same room. Distribution of light across ceilings in a given room that maintains lighting variety but avoids both dark spots and bright spots.	In the open office area on the second floor there are many areas where part of the ceiling is more than 10 times brighter than another section of ceiling in the same room. This is due to the use of direct/indirect fixtures being placed directly below air ducts. Because the luminaire is only inches below the ductwork the duct is in some cases 15 times brighter than nearby sections of the ceiling that are blocked by the ductwork.

Feature L06 Model Results Summary

The MOS meets Part One of Feature L06 and earns a point for achieving at least four of the six requirements for visual balance. In most areas the project met all six of the features. There were several areas on the first floor where surfaces were more than three times brighter than adjacent surfaces but most, if not all these instances could be corrected by adjusting the illuminance by dimming a particular fixture in order to meet the ratios required by Feature L06. Figure 34 uses arrows to illustrate two sections of ceiling where the one area exhibits a greater than 10 times higher luminance than an area beside it. This is due to the use of direct/indirect fixtures placed directly below ductwork causing an uneven lighting distribution across the ceiling.

Figure 35. Example of ceiling luminance ratio exceeding requirements of Feature L06. Red arrows point to two sections of ceiling where the ratio is greater than ten times greater or lesser luminance June, 2019.

The model achieved this feature without any changes so there are no additional costs required to achieve this feature.

No studies relating to quantitative benefits of maintaining luminance balances were found during a computer based literature search. Table 32 lists four studies that reported that luminance ratios far in excess of those required by Feature L06 had no impact on productivity.

Table 32. Productivity benefits of maintaining luminance balances in Feature L06.

Study	**Productivity Increase Converted to Dollars**	**Reference**
Cushman et al.	$0.00	(Cushman et al., 1984)
Parpairi et al.	$0.00	(Parpairi et al, 2002)
Linney	$0.00	(Linney, 2008)
Osterhaus	$0.00	(Osterhaus, 2002)

Table 33 lists two studies that showed that slowly dimming lights over a period of 30 minutes or more as required by Feature L06 Part 1 Option D, had no impact on productivity.

Table 33. Productivity benefits of slowing the dimming rate to meet Feature L06 requirements.

Study	**Productivity Increase Converted to Dollars**	**Reference**
Juslén 2007	$0.00	(Juslén, 2007)
Newsham et al	$0.00	(Newsham et al., 2006)

In addition to the quantitative analysis of the benefits of visual balance, the research used for this thesis reported a number of qualitative benefits. Table 34 lists five studies that reported the following ancillary benefits that were not included in the quantitative analysis above:

Table 34. Ancillary benefits of maintaining illuminance balances in Feature L06.

Study	Financial	Well-Being	Health	Safety	Cognitive Function	Performance	Reference
UK Health and Safety Executive				X			(Great Britain & Health and Safety Executive, 2002)
Wibom & Carlsson			XX			X	(Carli et al., 2008)
de Vries et al			X			X	(de Vries et al., 2018)
Carli et al.	X						(Carli et al., 2008)
Cushman et al.			X		X		(Cushman, 1984)
	1	0	4	1	1	2	

Table 35 shows one study that reported ancillary benefits relating to slow dimming speed.

Table 35. Ancillary benefits of controlling dimming speed.

Study	Financial	Well-Being	Health	Safety	Cognitive Function	Performance	Reference
Creemers et al.		X X					(Creemers, van Loenen, Aarts, 2014)

Figure 36 shows the distribution of ancillary benefits related to maintaining luminance ration balances.

Figure 36. Distribution of reported ancillary benefits of maintaining luminance balance.

Feature L06 Analysis of Results

The model office space achieved Feature L06 but research indicating potential benefits of these rather restrictive luminance ratios has been refuted in a number of studies showing that building occupants can be productive and comfortable with luminance ratios more than 300 times greater than some of the more restrictive requirements of Feature L06. Although research points to some qualitative benefits relating to health and performance there is not enough quantitative research to establish significant financial benefits to an employer by implementing Feature L06. Although the model is able to achieve this feature without additional costs, Table 34 shows there are no significant cost savings over a ten-year period.

Table 36. Ten-Year costs and benefits of implementing Feature L06.

One-time costs required to achieve feature	Annual costs to maintain feature	Number of workers who can benefit from feature	Annual productivity benefits per employee	Annual productivity benefit total	Ten-year financial impact (Benefits minus costs)
$0.00	$0.00	215	None	None	None

Feature L07 – Electric Light Quality

This optional feature requires projects to consider characteristics of electric light used in the space such as color rendering, color quality and flicker frequency. Table 37 shows the requirements of Feature L07 as well as the results of the MOS analysis.

Feature L07 Model Results Summary

Analysis of the MOS fixture cut sheets and reflected ceiling plan show that none of the existing fixtures met a Color Rendering Index (CRI) higher than 90. Therefore, the model office space did not meet Part 1 of Feature L07. Excluding decorative, specialty and multi-purpose lighting, there were 26 fixture types in the MOS that have a CRI below 90 (for details see Appendix 2).

Table 37. Requirements of Feature L07 and results of model analysis.

<table>
<tr><th colspan="2">WSBv2 Feature</th><th colspan="2">Model Office Space Results</th></tr>
<tr><td colspan="4">L07 Electric Light Quality (Max 2 points)</td></tr>
<tr><td colspan="4">Part 1. Ensure color-rendering quality (1 point) - Electric lighting meets at least one of the following color-rendering requirements in occupied spaces. Decorative fixtures, emergency lights and other special-purpose lighting may be excluded from these requirements.</td></tr>
<tr><td colspan="4">Electric lighting meets one of the following requirements:</td></tr>
<tr><td>Legend</td><td>Model achieves feature with no changes necessary</td><td>Model achieves feature at little to no cost and effort</td><td>Model cannot achieve feature without considerable cost or effort</td></tr>
<tr><td>Metric</td><td>Threshold</td><td colspan="2" rowspan="4">None of the fixtures used in the MOS had a CRI higher than 90.</td></tr>
<tr><td>CRI</td><td>CRI>90</td></tr>
<tr><td>CRI, R9</td><td>CRI >80 with R9 > 50</td></tr>
<tr><td>IES TM-30-18</td><td>IES Rf ≥78, IES Rg ≥ 100, -1% ≤ IES Rcs,h1 ≤ 15%</td></tr>
<tr><td colspan="4">Part 2. Manage flicker (1 point)</td></tr>
<tr><td colspan="4">All electric lights (except decorative lights, emergency lights and other special-purpose lighting) used in regularly occupied spaces meet at least one of the following requirements for flicker:</td></tr>
<tr><td colspan="2">A. A minimum frequency of 90 Hz at all 10% light output intervals from 10% to 100% light output</td><td colspan="2">According to the lighting submittal fixture cut sheets, all installed fluorescent ballasts are electronic ballasts with operating frequencies between 42,000 Hz and 52,000 Hz.</td></tr>
<tr><td colspan="2">B. LED products with a low risk level of flicker of less than 5%, especially below 90 Hz operation as defined by IEEE standard 1789-2015 LED</td><td colspan="2">Electronic drivers used in model space operate at 240 Hz.</td></tr>
</table>

The MOS did achieve Part B and earn one point for meeting the flicker requirements of Feature L07. The fluorescent fixtures utilized Lutron Ecosystem H Series ballasts, Lutron 5-series ballasts and Phillips Advance Optanium ballasts, all of which operate at 42,000 Hz or higher. These electronic ballasts operate at frequencies more than 466 times higher than the minimum frequency required by Feature L07 (for details see Ancillary Appendix). For LED fixtures, the model space uses Lutron Hi-Lume 1% EcoSystem drivers that operate at 240 Hz (for details see Ancillary Appendix).

There were 26 fixture types installed in the model office space that did not meet the minimum CRI requirements of Feature L07. The CRI for each fixture type that did not meet a CRI of 90+ ranged between 80 and 85. Of the 26 fixture types that did not meet L07 eight of them had the option to be upgraded to a 90+ CRI at the time of purchase, while 18 fixture types did not offer the option. In total, there were 494 fixtures that would need to be upgraded in order to achieve Part 1 for Feature L07 (Appendix 2). An Internet-based search of LED fixtures with an option to upgrade from a lower CRI to a 90+ CRI revealed the average cost of the first 20 fixtures analyzed was $22 per fixture. If the lighting had been upgraded to meet feature L07 the total estimated cost would have been approximately $10,868.

In addition to the upfront costs of upgrading fixtures to meet Part One of Feature L07 there would also be higher electricity costs because high CRI fixtures are usually less efficient than lower CRI fixtures (Waveform Lighting, 2019). It is not uncommon for a high CRI LED fixture to deliver 20% fewer lumens per watt when compared to 80 CRI fixtures (USAI Lighting, 2011). However, as LEDs are constantly improving, for the purpose of this analysis it will be assumed that the higher CRI fixtures required by Feature L07 will be 10% less efficient than the existing LED fixtures. Assuming 0.85 Watts per square foot and 13 cents per kWh the energy cost difference caused by the less efficient higher CRI fixtures would be $1,862 per year.

Table 38 shows the results of six studies that determined there were no productivity benefits from high CRI or full spectrum lighting for typical office workers (Appendix 1).

Table 38. Productivity related benefits of high CRI and/or full spectrum lighting in office buildings.

Study	Productivity Increase Converted to Dollars	Reference
Hedge	$0.00	(Hedge, 2016)
Fisk and Rosenfeld	$0.00	(Fisk and Rosenfeld, 1997)
Veitch	$0.00	(Veitch et al, 1995)
Carli et al	$0.00	(Carli et al., 2008)
Veitch 1997	$0.00	(Veitch, 1997)
Veitch 2001	$0.00	(Veitch, 2001)

There is evidence that when compared to subjects working under low frequency flicker, significant productivity improvements could be achieved as a result of replacing lighting with fixtures that produce higher frequency flicker rates. Table 39 shows the two productivity studies found that give quantitative results relating to productivity as a result of eliminating low frequency flicker. The average potential productivity increase of these studies is $1,544 per employee per year.

Table 39. Productivity related benefits of managing flicker.

Study	Productivity Increase Converted to Dollars	Reference
Kuller and Laike 1998	$2,600.00	(Loftness & Hartkopf, 2003)
Bommel et al.	$487.50	(Bommel et al., 2002)

In addition to the quantitative analysis of how CRI and Flicker affect productivity, the research used for this thesis listed several qualitative benefits. There were eight studies and reports that listed the following ancillary benefits that were not included in the quantitative analysis above (Table 40).

Table 40. Ancillary benefits of high CRI/full spectrum light sources in office buildings.

Study	Financial	Well-Being	Health	Safety	Cognitive Function	Performance	Reference
Boyce						X	(Boyce, 2003)
Nickerson						X	(Nickerson, 1960)
ASTM						X	(ASTM, 1996)
Blackwell						XX	(Blackwell, 1985)
Maas et al.						XX	(Maas et al, 1974)
Abdou					X		(Abdou, 1997)
Bommel et al.				X			(Bommel et al., 2002)
Knez 2001		X			X	X	(Knez, 2001)
	0	1	0	1	2	8	

Table 41 shows nine studies and reports that listed the following ancillary benefits related to reducing low frequency flicker.

Table 41. Ancillary benefits of managing flicker.

Study	Financial	Well-Being	Health	Safety	Cognitive Function	Performance	Reference
UK Health and Safety Executive			X	X			(Great Britain & Health and Safety Executive, 2002)
Veitch & Newsham						X	(Veitch & Newsham, 1998)
Wilkins et al.		X	X X				(Clements-Croome, 2006)
Lindner and Kropf			X X X				(Lindner and Kropf, 1993)
Boyce et al.						X	(Boyce et al., 2003)
Rey and Rey					X		(Rey & Rey, 1965)
Veitch et al.			X X			X	(Veitch, 2006)
Bullough et al.	X						(Bullough et al., 2011)
Bommel et al.		X X X	X			X	(Bommel et al, 2002)
	1	4	9	1	1	4	

Figure 37 shows the distribution of ancillary benefits of high CRI/Full spectrum light sources as well as benefits of reducing low frequency flicker.

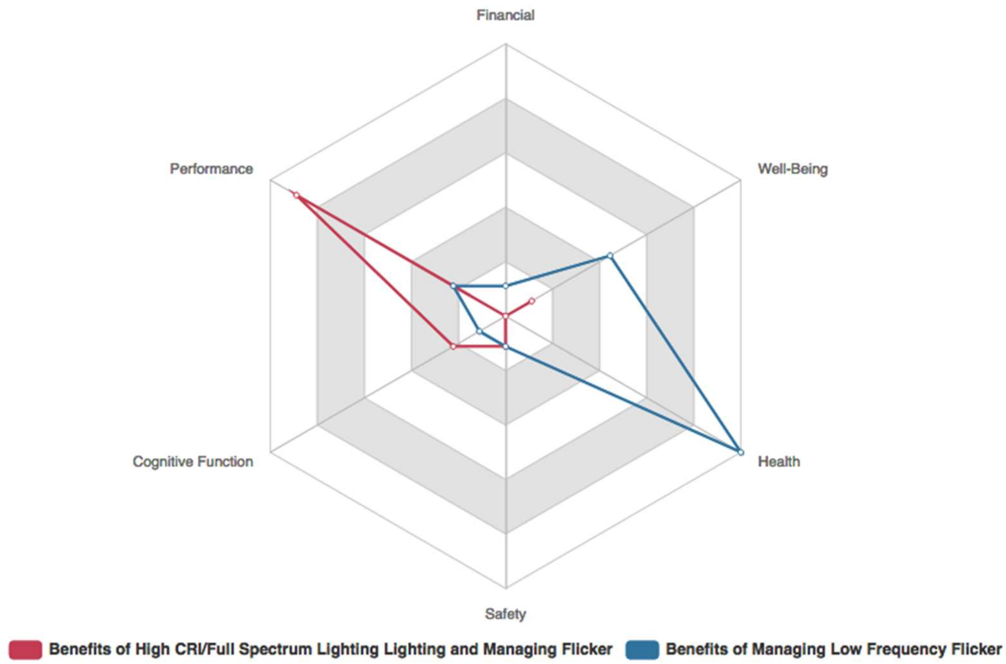


Figure 37. Distribution of ancillary benefits relating to high CRI and flicker reduction.

Feature L07 Analysis of Results

In order for the MOS to achieve Part One of Feature L07 it would have required additional costs of $10,868 for higher CRI fixtures. Additionally, due to the lower efficiency of high CRI fixtures there would have been additional energy costs of $1,862 per year in order to achieve the same light levels currently found in the MOS. Because there are no quantitative studies showing any economic benefit of high CRI or full spectrum lighting for typical office workers, implementing Part one of Feature L07 would have ended up costing the model office space $29,484 in additional fixture and energy charges over a ten year period.

Although there does appear to be economic benefits of eliminating low frequency flicker, the MOS was designed and built using high frequency ballasts and LED drivers that far exceed the requirements of Part Two Feature L07. There are no additional charges required to meet this feature but there are also no additional benefits available for workers. Table 42 shows the 10-year cost-benefit analysis of implementing Feature L07.

Table 42. Ten-Year costs and benefits of implementing Feature L07.

Feature L07	One-time costs required to achieve feature	Annual costs to maintain feature	Number of workers who can benefit from feature	Annual productivity benefits per employee	Annual productivity benefit total	Ten-year financial impact (Benefits minus costs)
Part 1 CRI	$10,868.00	$1,861.60	215	0	0	-$29,484.00
Part 2 Flicker	0	$0.00	0	$1,543.75	0	0

Feature L08 – Occupant Control of Lighting

This optional feature requires projects to implement lighting strategies that consider the personal preferences of users. Table 43 shows the requirements of Feature L08 as well as the results of the MOS analysis.

L08 Model Results Summary

The MOS automatically earned one point for Part Two because it already provided a task light for workers who asked for one. The MOS also achieved L08 Part One Section A because the lighting control system is tunable and can be programmed to meet circadian and visual requirements of office workers. The MOS did not earn a point for Part One because the light fixtures do not meet Part One Section B due the fixtures having a static CCT that cannot be tuned or adjusted by building occupants. This would require replacement of most of the light fixtures in the MOS.

Table 43. Requirements of Feature L08 and results of model analysis.

WSBv2 Feature	Model Office Space Results	
L08 Occupant control of lighting environments (Max 2 points)		
Part 1. Enhance occupant controllability (1 point)		
Ambient lighting systems in regularly occupied spaces meet the following requirements:		
Legend - Model achieves feature with no changes necessary	Model achieves feature at little to no cost and effort	Model cannot achieve feature without considerable cost or effort
Part 1. A. Light systems are tunable and automated to meet the circadian and visual requirements of the occupants.	Existing lighting control system is tunable and capable of being automated. It has not been programed specifically to meet circadian requirements, but it is capable of time clock events, 30-minute fade, multiple scene programming etc.	
B. Occupants have control of light levels, color temperature and color of electric light in their immediate environment and can override automated settings for at least 30% of operating hours.	Many areas are not controllable by occupants in the current set up. Light levels are controllable, but fixtures are not capable of changing color temperature, or color changes.	
Part 2. Provide supplemental lighting (1 point) - The following requirements are met:		
A. Supplemental light fixtures meet the following:		
1. Can increase the light level on the task surface to at least twice the recommended light levels based on the reference used to meet Part 1: Light Levels for Visual Acuity in Feature L02: Visual Lighting Design.	Task lighting is available to workers who ask for it. Task lighting is capable of increasing illumination on the work surface to at least twice the recommended light levels of the IES Lighting Handbook 10th Edition.	
2. Are provided at no cost upon request.	There is no additional cost for workers who request task lights.	
B. Requests for supplemental light fixtures are met within eight weeks of request.	Fixtures are available to workers in less than 8 weeks from date of request.	

In order to achieve Part One Section B the existing lighting control system needs to be upgraded to enable the system to change the color and intensity of light in each occupied area. To enable users to control the light level, CCT and color of light, the number of controls will need to increase by more than double. For an estimate to upgrade the existing Lutron Quantum lighting control system to enable color tuning and color changing, a budgetary quote was obtained from the manufacturer of the existing lighting control system. The quote for the lighting controls upgrade required to achieve Feature L08 was $3,000 (see Ancillary Appendix for details).

In order to determine the cost to upgrade the existing lighting to fixtures that meet the requirements of Feature L08 a lighting fixture manufacturer's representative was contacted to provide a budgetary quote. Two options were requested for fixture upgrades with one quote for fixtures that meet the requirements of Part 1 Section B that are CCT tunable and color changeable, and another quote for tunable white (adjustable CCT only) fixtures that do not meet the requirements of Feature L08. The tunable white option will be discussed in the Feature L08 Analysis of results section.

The manufacturer's representative estimated the original cost of the fixtures, as built, to be approximately $225,000. If the lighting had originally been upgraded to meet Feature L08 the cost would have been an additional $202,500 for the fixtures, plus $64,125 for DMX controls and $10,000 for five days of additional commissioning for a total price of $501,625. Because the existing lighting and controls system utilizes digital ballasts and drivers with additional wires for digital communication, there would not be a significant cost difference for the labor component to upgrade from the existing to a system capable of achieving Feature L08 (for details regarding fixture upgrades see Appendix 2).

For L08 Part 2, the model office space already provided high lumen task lighting for most workstations so there would be little to no additional cost necessary to meet Part 2 of this feature. A Carnegie Melon study analyzed the costs and energy savings associated with adding task lighting for office workers and found that by adding task lighting the general overhead lighting could be greatly reduced (Loftness, Ap, Cochran, & Srivastava, 2013). The study found that a high quality task light that meets the requirements of the WBSv2 would cost $164 per employee but it would save $72 per year in lighting energy savings and operations and maintenance costs leading to a 3 year payback without factoring in any increases in worker productivity (Loftness et al, 2013). The Carnegie Melon study calculated the health and productivity benefits of having controllable task lighting and found that the impact for each employee would be $14 in health benefits, $178 in productivity increases and $6 in reduced absenteeism for a total of $198 in health and productivity benefits per employee per year (Loftness et al, 2013). With energy savings and employee health and productivity benefits the payback period for adding task lighting is 8 months.

Estimates of the effects of CCT on worker productivity vary greatly, ranging from having no effect, to increasing productivity more than $15,000 per employee per year. Table 44 shows the predicted change in worker productivity across eight studies. The Mills study was included in the table to show that certain CCT conditions are estimated to provide very large increases in productivity but this study will not be included in the final estimated results because the study used 17,000 K fixtures which are not feasible in most office buildings (Mills, Tomkins, & Schlangen, 2007).

Table 44. Productivity related benefits relating to tunable lighting and CCT for office workers.

Study	Productivity Increase Converted to Dollars	Reference
Knez	$6,093.75	(Knez, 2001)
Mills et al. (This study is not included in the final estimate)	$15,762.50*	(Mills et al., 2007)
Ishii et al.	$2,031.25	(Ishii et al., 2018)
Juslen 2007	$4,631.25	(Juslén, 2007)
Veitch & McColl	$0.00	(Veitch & McColl, 1995)
Boray et al.	$0.00	(Boray et al., 1989)
Sivaji et al.	$0.00	(Sivaji et al., 2013)
Shamsul et al.	$5,443.75	(Shamsul et al., 2013)

Figure 37 shows the distribution of research results from Table 44. The results range from $0.00 to $6,094 with a median value of $2,031 and a mean value for productivity increases as a result of tunable CCT of $2,600 per employee per year.

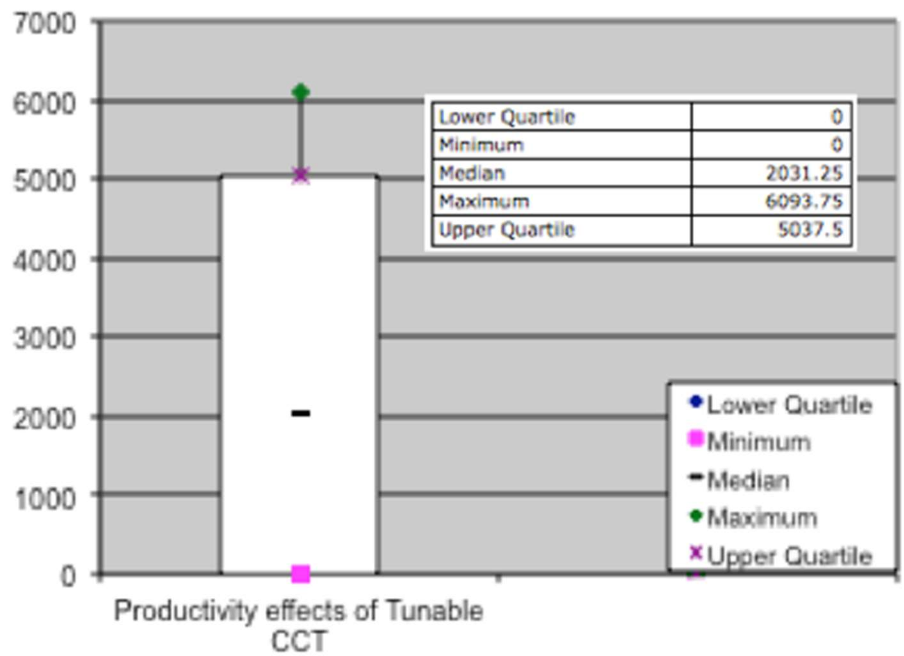


Figure 38. Distribution of quantitative estimates of productivity increases as a result of tunable CCT.

Research estimates of productivity increases as a result of providing personal lighting controls to office workers are listed in Table 45.

Table 45. Productivity related benefits relating to personal lighting controls for office workers (Appendix 1).

Study	Productivity Increase Converted to Dollars	Reference
Juslén	$3,656.25	(Juslén et al., 2007)
Veitch & Newsham	$0.00	(Veitch & Newsham, 2000)
Study of clerical workers	$5,687.50	(Hughes, 1978)
Barnaby	$1,096.88	(Loftness & Hartkopf, 2003)
Lovins	$2,275.00	(Edwards et al., 2002)
Kats	$5,768.75	(Kats, 2003)
Nishihara	$4,468.75	(Loftness et al, 2013)

Figure 38 shows the distribution of research results from Table 45. The results range from $0.00 to $5,769 with a median value of $3,656 and a mean value for productivity increases as a result of personal lighting controls of $3,279 per employee per year.

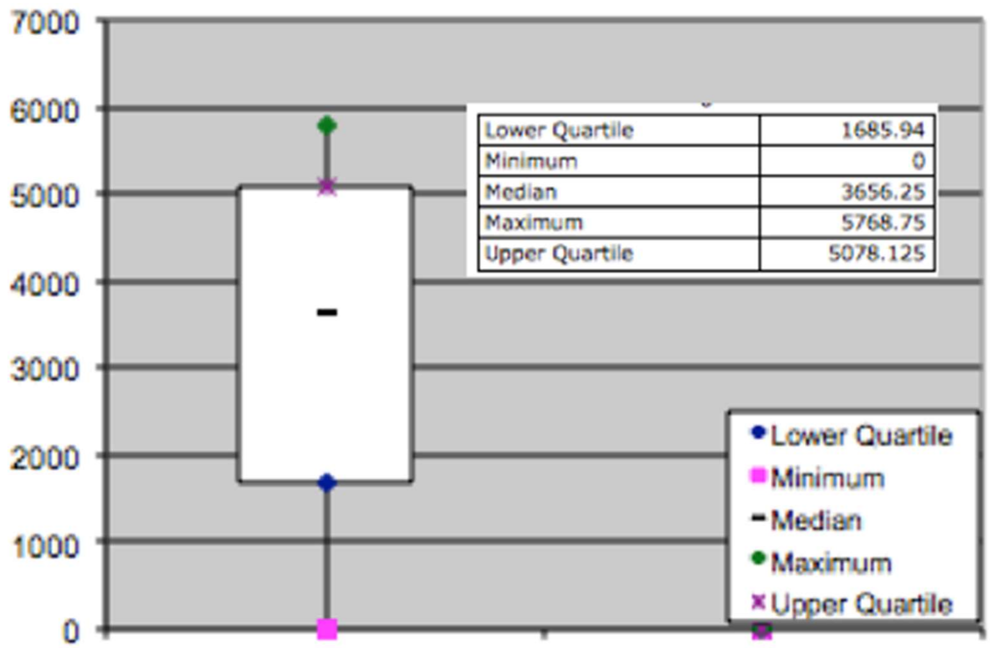


Figure 39. Distribution of quantitative estimates of productivity increases as a result of personal lighting controls.

No quantitative studies reporting worker productivity increases as a result of changing the hue and saturation of light were located but three studies were found reporting that the color of light had no impact on productivity and are listed in Table 46.

Table 46. Productivity related benefits relating to light color.

Study	Productivity Increase Converted to Dollars	Reference
Knez	$0.00	(Knez, 2001)
Knez & Kers	$0.00	(Knez & Kers, 2000)
Knez & Enmarker	$0.00	(Knez & Enmarker, 1998)

In addition to the quantitative analysis of the benefits of tunable CCT fixtures, the research used for this thesis mentioned several qualitative benefits. Table 47 lists 12 studies that reported ancillary benefits that were not included in the quantitative analysis above.

Table 47. Ancillary benefits of tunable lighting and CCT in offices (for details see Appendix 1).

Study	Financial	Well-Being	Health	Safety	Cognitive Function	Performance	Reference
Mills et al.	X		X			XXX	(Mills et al., 2007)
Askipoor et al.					X	XXX	(Askipoor et al. 2018)
Juslén		X				X	(Juslén et al., 2007)
McCloughan et al.		X				X	(McCloughan et al, 1999)
Knez	X	X				X	(Knez, 2001)
Knez					XXX	XXX	(Knez, 2001)
Askipoor et al.		XX	X	X	XX	XXXX	(Askipoor et al. 2018)
Wei et al.	XX	XX				XX	(Wei et al., 2014)
Baron et al.	X	XX			X	XX	(Baron et al. 1992)
Deguchi and Sato					X	XX	(Burattini, 2019)
Viola		X			X	XX	(Mills et al. 2007)
Chellappa et al	X	X			X	XXXX	(Chellappa et al. 2011)
	6	11	2	1	10	28	

In addition to the quantitative analysis of the benefits of personal lighting controls, the research used for this thesis mentioned several qualitative benefits. Table 48 lists 12 studies that reported ancillary benefits that were not included in the quantitative analysis above.

Table 48. Ancillary benefits of personal lighting controls in offices (Appendix 1).

Study	Financial	Well-Being	Health	Safety	Cognitive Function	Performance	Reference
DYG Inc. Study for Knoll	XX						(DYG, Inc., 1998)
Bergs	XX		X			X	(Bergs, 2002)
Juslén & Tenner	X						(Juslén & Tenner, 2005)
Küller et al.		XX					(Küller et al., 2006)
Newson & Veitch	X	X					(Veitch & Newsom, 2000)
Leaman and Bordass						X	(Leaman & Bordass, 1999)
Boyce et al.					XX		(Carli et al., 2008)
Hoffmann et al.		X				XXX	(Küller et al., 2006)
Barnes	XX					X	(Clements-Croome, 2006)
Veitch & Newsom	X						(Veitch & Newsham, 2000)
Simpson	XX					X	(Clements-Croome, 2006)
Cakir and Cakir	X X						(Loftness et al, 2013)
	13	4	1	0	2	7	

In addition to the quantitative analysis of the benefits of color changeable fixtures, the research used for this thesis mentioned some qualitative benefits. Table 49 lists three studies that reported ancillary benefits that were not included in the quantitative analysis above.

Table 49. Ancillary benefits of adjustable light color on office workers.

Study	Financial	Well-Being	Health	Safety	Cognitive Function	Performance	Reference
Figueiro					X	X	(Figueiro, 2018)
Chung and Pease			X			X	(Chung & Lu, 2003)
Sahin et al.					XX	XX	(Sahin et al. 2014)
	0	0	1	0	3	4	

Figure 40 shows the distribution of ancillary benefits of Tunable CCT fixtures, personal lighting controls and color changing fixtures (Appendix 1).

Feature L08 Analysis of Results

The existing lighting control system already provides personal controls for all workers on the 1st floor and all offices and conference rooms on the second floor. The controls upgrade required to achieve Feature L08 will provide personal controls for an additional 160 employees working in the 2nd floor open office areas. It is important to note that the existing lighting control system cost in excess of $100,000 and included digitally addressable ballasts and drivers.

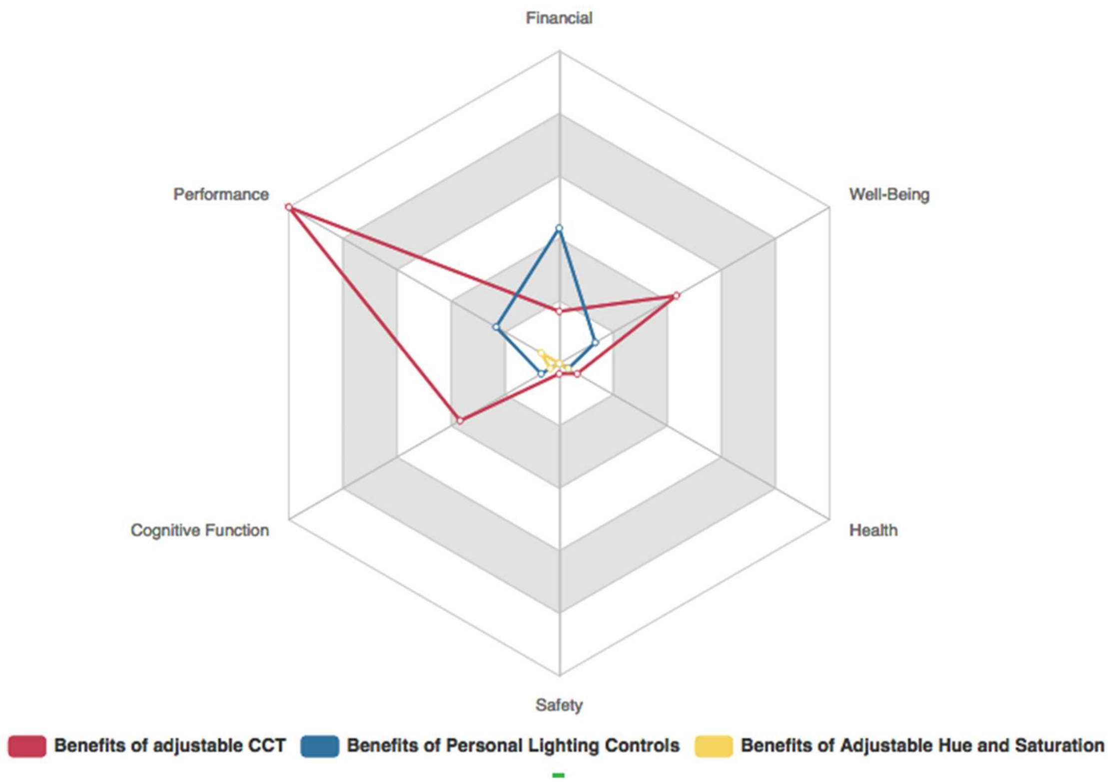


Figure 40. Distribution of ancillary benefits reported for lighting parameters associated with Feature L08.

To determine the cost differential between the original design and a design that achieves Feature L08, a credit for the ballasts and drivers was applied back to the original system, and then additional lighting controls were added to allow for color/CCT control and to ensure personal dimming control for all regularly occupied spaces.

Tunable CCT/color changing light fixtures will impact all workers as there are currently no adjustable CCT/color changing fixtures in the model office space and they are required in all regularly occupied spaces in order to achieve Feature L08. As mentioned previously, the quote for the fixtures included the additional start up and DMX controls necessary to tie the new fixtures in with the existing lighting controls system. The mean predicted productivity increase for tunable CCT fixtures is $2,600 per employee per year. There is not enough compelling research indicating that color changeable fixtures enhance productivity above and beyond the increases predicted from the use of tunable CCT fixtures. Color changeable fixtures are more expensive and require a more advanced lighting control system but adding color changing capabilities on top of tunable CCT doesn't appear to have productivity advantages. For the model office space, in order to achieve Feature L08 Part 1 B the fixtures would have cost an additional $276,625 above the cost of the original lighting in the MOS. If the MOS installed tunable CCT fixtures instead of color changing fixtures the expected productivity increases would be the same and it would cost $107,875 less.

The task lights save $72 in energy for each worker and add an additional $198 per person per year in productivity and health benefits. The majority of workers already have tasks lights in the current model so no there would be no additional costs required to achieve Part 2 of Feature L08 and there would be no additional benefits. If seeking to maximize the benefits of Feature L08 above and beyond the minimum requirements, each additional task light added would cost an additional $164 while providing $270 in benefits from reduced energy consumption, lower healthcare costs and increased productivity.

Table 50 shows the ten-year costs and productivity related benefits of Feature L08. The table shows that rather than purchasing fixtures that satisfy Feature L08, CCT tunable (rather than color changing) fixtures would save more than $107,000 in up-front costs while realizing the same benefits as fixtures that meet Feature L08. Table 50 shows that personal controls would benefit 160 workers on the second floor who currently did not have access to personal controls. Part One section B would benefit all 215 workers in the MOS because there are currently no tunable CCT fixtures. The MOS already achieved Part Two because approximately 80% of workers already have task lighting at their workstations. Table 50 shows the potential benefits of maximizing the benefits of task lighting by providing task lighting to all workers in the space.

Table 50. Ten-year costs and benefits of implementing Feature L08.

Feature L08	One-time costs required to achieve feature	Annual costs to maintain feature	Number of workers who can benefit from feature	Annual productivity benefits per employee	Annual productivity benefit total	Ten-year financial impact (Benefits minus costs)
Part 1 Section A (Personal Controls)	$3,000	$0.00	160	$3,279	$524,640	$5,243,400
Part 1 Section B (Fixtures)	$276,625	$0.00	215	$2,600	$559,000	$5,313,375
Tunable CCT Only	$168,750	$0.00	215	$2,600	$559,000	$5,421,250
Part 2. Task lights Minimum feature requireme nt	$0.00	$0.00	0	$0.00	$0	$0.00
Task Lights – Maximize benefits	$164.00 per light	-$72 per task light per year	43	$198	$8,514	$109,048

Chapter IV

Discussion

There is a plethora of evidence that several lighting parameters significantly impact worker productivity. The extent of productivity improvements has been debatable as estimates vary widely. Taking available research and developing mean estimates for each lighting parameter provides the most accurate understanding of the relationship between lighting parameters and productivity.

The purpose of this study is to help designers and building owners make better design decisions that help maximize worker performance though an improved luminous environment. To illustrate the costs of upgrading a building to meet all of the features of the WBSv2, a model office space was used to determine the financial impact. The MOS automatically achieved at least one point in all eight features. The MOS automatically earned both prerequisites and 10 out of a total of 14 points as originally designed. In order to achieve the remaining available features it would have required upgrades totaling approximately \$326,641 with \$279,625 required just to achieve one point for Feature L08. While that may seem like a large expenditure to achieve one point, it is estimated that the ten-year benefits of implementing the minimum requirements to achieve Part 1 of Feature L08 could be as high as \$10,500,000. According to the mean estimates of increased productivity resulting from each feature, the anticipated financial benefits for achieving the minimum requirements of each of the features would be \$1,146,223 per year with the vast majority of those benefits resulting from personal dimming controls and tunable CCT fixtures. Table 51 summarizes the costs and predicted benefits of implementing each of the lighting features of the WBSv2 based on the MOS.

Table 51. Estimated incremental costs and benefits of incorporating the minimum requirements of each feature of the WBSv2 in the model office space.

Feature	Estimated cost to implement	Estimated incremental annual costs to maintain feature	Estimated annual benefits	Ten-year return on investment
Feature L01 Light Exposure and Education	$400	$0.00	0.00	-$400
Feature L02 Visual Lighting Design	Achieved as originally built	$0.00	$0.00	$0.00
Feature L03 Circadian Lighting Design	Achieved as originally built	$0.00	$0.00	$0.00
Feature L04 Glare Control	$12,240	$0.00	$62,582.78	$613,587.80
Feature L05 Enhanced Daylight Access	Achieved as originally built	$0.00	$0.00	$0.00
Feature L06 Visual Balance	Achieved as originally built	$0.00	$0.00	$0.00
Feature L07 Electric Light Quality	$10,868.00	$1,861.60	$0.00	-$29,484.00
Feature L08 Occupant Control of Lighting Environments	$279,625	$0.00	$1,083,640	$10,556,775
Entire Lighting Concept Category	$303,133	$1,861.60	$1,146,222.78	$11,140,878.80

Using the median predicted productivity benefits of each feature and looking for opportunities in the model office space to maximize productivity above and beyond the minimum requirements necessary to achieve each feature, Table 52 shows that for an investment of $191,442 the MOS could implement lighting upgrades that could potentially be worth as much as $15,016,279 over a ten-year period.

Table 52. Estimated costs and benefits of maximizing the benefits (exceeding the minimum requirements necessary to achieve the feature) of each feature of the WBSv2 in the model office space.

<table>
<tr><th>Feature</th><th>Estimated cost to implement</th><th>Number of workers affected by improvement</th><th>Estimated annual benefits</th><th>Ten-year return on investment</th></tr>
<tr><td>Feature L01 Light Exposure and Education</td><td>$400</td><td>29</td><td>$160,508.91</td><td>$1,604,649.10</td></tr>
<tr><td colspan="5">Notes – L01: Swap daylit conference rooms with 1st floor southern open office area to give workers access to daylight and views.</td></tr>
<tr><td>Feature L02 Visual Lighting Design</td><td>$0.00</td><td>36</td><td>$61,320.60</td><td>$613,206.00</td></tr>
<tr><td colspan="5">Notes – L02: Select fixture with either higher lumen output or lower lumen depreciation, or use lighting controls to set high end trim in order to reduce lumen depreciation to ensure workers will continue to meet minimum light level requirements of L02.</td></tr>
<tr><td>Feature L03 Circadian Lighting Design</td><td>$0.00</td><td>36</td><td>$139,159.80</td><td>$1,391,598.00</td></tr>
<tr><td colspan="5">Notes – L03: These values are in addition to the estimated benefits from Feature L02. If lighting were brought back into compliance of Feature L02 with the original fixture, there would be benefits for not only lighting for visual acuity, but also lighting for circadian entrainment. If benefits had not been split between Feature L02 and L03 the predicted 10-year benefits of L03 for the 36 workers would be $2,004,804.00.</td></tr>
<tr><td>Feature L04 Glare Control</td><td>$12,240.00</td><td>22</td><td>$63,936.78</td><td>$627,127.18</td></tr>
<tr><td colspan="5">Notes – L04: Replace high UGR fixture in fabrication room (impacts 13 workers) and implement shade adjustments (impacts 9 workers) multiple times per day.</td></tr>
</table>

Feature L05 Enhanced Daylight Access	Already maximized under L01	N/A	5,534.79	N/A
Notes – L05: In order to maximize Feature L01 all workers in windowless areas would be moved near a window. There would be no additional benefit for Feature L05 if L06 were maximized.				
Feature L06 Visual Balance	$0.00	$0.00	$0.00	$0.00
Notes – L06: The model office already achieved this feature. However, there doesn't appear to be enough research showing productivity improvements to counteract the estimates stating there are no benefits of reducing luminance ratios to those required by Feature L06.				
Feature L07 Electric Light Quality	$10,868 for new fixtures plus $1,861.60 per year for higher energy cost due to lower efficiency of higher CRI fixtures.	215	$0	$-29,484
Notes – L07: From a productivity perspective, the way to maximize the benefits of this feature is to not implement it for the MOS. Taking ancillary benefits into account there may still be justification for implementation. Because there are significant costs but no predicted benefits, the values for this feature will not be included in the totals below.				
Feature L08 Occupant Control of Lighting Environments	$178,802	160 for personal controls, 215 for tunable CCT and 43 for task lights	$1,092,154	$10,773,698
Notes – L08: To maximize the benefits from Feature L08 it would be more beneficial to forgo the point for Part 1 because it requires color changing fixtures. Instead, the use of tunable CCT fixtures will provide the same productivity benefits				
Entire Lighting Concept Category	$191,442	215	$1,417,080.09	$15,016,278.80

Research Limitations and Caveats

Literature on the topic of how lighting impacts productivity reports a wide range of results. It was observed during the course of this research that long-term field studies of existing buildings tend to show larger productivity increases than many of the short-term lab studies. This may or may not be a result of the impact light has on an individual over the long term. For instance a two-day lab study cannot measure all of the benefits of improved sleep over a period of months or years. If an employee moves from a windowless basement to an office with large windows, quality views and natural circadian lighting and it causes them to sleep an extra 40 minutes per night, the extra sleep could impact their health, fitness and performance over the course of several months.

Another potential explanation for the varied results in many of the existing studies relating to lighting and worker performance is due to the fact that many of the studies are small in size and unlikely to identify small increases in productivity (Fisk & Rosenfeld, 1997). Additionally, the majority of research subjects have been young adults and lighting is expected to have a larger influence on the performance of older adults (Fisk & Rosenfeld, 1997).

Potentially some of the studies used in this thesis may have been impacted by the "Hawthorne Effect", the effect the study itself has on the subject being studied where the act of being observed can lead to improved performance (Clements-Croome, 2006). Research resulting in increased productivity as a result of lighting improvements is sometimes discounted because early studies of worker productivity found that output improved regardless of which luminous parameter or value was being tested (Clements-

Croome, 2006). This has led some to believe that worker performance will improve solely because the worker is being monitored and any productivity increase may reverse or subside once the worker is no longer being studied. The “Hawthorne Effect” has been disputed and attempts to overcome the effect may actually be skewing research results and causing some researchers to miss small productivity increases (Gottfredson, 1996; Wickström & Bendix, 2000).

The cost information to upgrade lighting and controls from a traditional building to one that meets the WBSv2 lighting features was based on one building. An attempt was made to select a building that would be representative of the type of office buildings likely to be considered for an upgrade to the WBSv2. Selecting a different building as a base model would have made the costs and benefits higher or lower depending on the building selected and the results could vary significantly from the results of this study.

Due to the number of topics included in this thesis it was not possible to locate and include every study performed on a particular topic. An attempt was made to spend an equal amount of time researching each major topic but some topics yielded dozens of studies, while other topics yielded very few. There is no question that given more time additional research could be located that might change the mean values considerably.

Another consideration about the studies found during the literature review is publishing bias. It is possible that research that found no measurable benefits was not reported and that could skew the benefits of some topics higher than they would be in reality. The goal of this thesis is to provide enough information that designers and building professionals will start to consider lighting and controls as an investment, and in doing so improve the health and well-being of building occupants.

Questions for Further Research

It appears that worker productivity continues to improve as illuminance increases at least to a point where the illumination is several times higher than current IES recommendations. At some point the performance and productivity improvements must stop and eventually decrease due to glare. A future study that tests the regression equation found while researching the benefits of Feature L02 for this thesis [5.57234 + 0.06532 (light level in foot candles)] may be able to verify the accuracy of this equation and also determine the upper limit where additional illuminance no longer leads to increased performance and improved productivity.

Another question that may be worthy of additional research is whether the CRI requirements of Feature L07 lead to benefits that outweigh the reduced efficiency of higher CRI lighting. The benefits of upgrading from an 85 CRI fixture to a 90+ CRI fixture may not be worth the additional energy costs.

A final question worth considering is whether the available points for the WBSv2 are weighted in such a manner that they are likely to have the greatest impact on building occupants. It appears that for the MOS the two most significant upgrades available to improve worker performance are personal lighting controls and tunable fixtures. The benefits of these two upgrades could potentially result in millions of dollars due to improved performance. These are also two of the most expensive options required to achieve a lighting feature in the WBSv2. With the potential impact and the high costs the WBSv2 does not incentivize designers to upgrade the controls and fixtures when both upgrades have been lumped into the same feature and when added together are only worth one point. Perhaps personal lighting controls and tunable fixtures could be split out into their own feature and the point value could be reevaluated in order to have a more significant impact on building occupants.

Conclusions

After analyzing existing literature to determine the potential value of luminous parameters addressed by the WBSv2, as well as the costs required to implement them, an analysis of the MOS predicts that an investment of $191,442 could lead to improved productivity valued at up to $1,417,080 per year. This amounts to a productivity increase of $6,591 per employee per year, or approximately 8% of the average salary of an office worker in the United States. Comparing this number to the previously discussed available research estimating the impact lighting can have on productivity, this value fell near the lower quartile (Figure 14).

This thesis set out to answer a number of questions. The first question was "Do the lighting features in the WBS have enough compelling scientific research to warrant productivity improvements being included in a cost/benefit analysis?" The answer to this question is that the majority of lighting features in the WBSv2 do have compelling evidence to warrant productivity benefits being included in a cost/benefit analysis. For details and references relating to each study see Appendix 1. The only feature that lacks compelling evidence that resulting increases in productivity will lead to a return on investment is Feature L06.

The second research question this thesis addressed was "Which lighting and/or controls improvements offer the greatest ROI once productivity improvements are included?" It is likely that Feature L01 would have the highest ROI, as there are little upfront costs required and there are significant increases in productivity predicted. In the past, a business's senior management was mostly likely to occupy windowed offices but with the evidence that workers are likely to be roughly 7% more productive it is clear that offices should be designed to allow as many building occupants to have access to windows and views as possible. Feature L02 would likely have the second highest ROI. With results of the linear regression showing that productivity increases 0.07% with each additional foot-candle there is strong evidence that providing workers with brighter work areas will offer a significant payback.

The third research question was "Are the benefits of upgrading lighting features to meet the WBSv2 worth the cost of implementation?" Each feature of the WBSv2 was analyzed to determine whether evidence exists supporting the likelihood that the feature provides financial benefits to an employer. This study determined that each feature of the WBSv2 is likely to provide financial benefits with the exception of Feature L06 Visual Balance. While studies relating to luminance ratios suggest there are no negative productivity impacts at ratios much higher than prescribed by the WBSv2, there are a number of ancillary benefits for this feature that may justify implementation regardless of financial impact to an employer. There were other features that have requirements for lighting parameters that are known to provide financial benefits for one part of the feature while another part requires lighting upgrades that don't have significant research justifying their inclusion. For example, Feature L07 Part 1 requires high CRI fixtures, which don't have a significant impact on productivity unless work tasks require fine color discrimination. Part 2 of Feature L07 requires elimination of low frequency flicker, which studies suggest does impact worker productivity. Overall, the WBSv2 lighting requirements provide an excellent framework to ensure the most important and valuable lighting parameters are addressed.

If a WBSv2 Certification is not an option for a particular project, designers and building professionals can select individual features or portions of features and compare them to the benefits evaluated in this thesis to help them conduct a cost benefit analysis. Building professionals can also evaluate the research and data in this thesis to develop a lighting plan that limits up-front costs while maximizing productivity benefits.

Combining natural light and views with a good lighting and controls system that minimizes glare and flicker while providing the proper spectrum throughout the day, is perhaps the least expensive way to increase worker productivity by up to $10,000 per employee per year.

Appendix 1

Source Data, References and used for Quantitative and Qualitative Analyses

Table 53. Source Data and References used for Quantitative and Qualitative Analyses – Studies of Workplace Impact on Productivity From Lighting Improvements

Research Relating to Productivity Impacts Due to Workplace/Lighting Improvements

Notes: An annual salary of $81,250 ($39.06/hour) was used to calculate financial impact. A building Size of 207,740 was used to standardize calculations. For number of employees per building 151 square feet per employee was used. Each extra minute of sleep on average over the course of a year is worth $46.83 to an employer. Absenteeism costs employers an average of $1,685 per employee per year. A one percent improvement in cognitive performance will be counted count as half as valuable as a one percent improvemnt in overall worker performance. See "methods" for more info.

Studies of Workplace Impact on Productivity - The Following Research Shows Estimated Productivity Increases Due to Improving Workspace (Lighting, HVAC, Accoustics, etc.)

Study Name or Author	Research Findings	% Increase Per Employee Per Year	Value selected	Formula used	Converted to $/ employee/ year	Reference	Notes
Lab studies and literature reviews							
GSA Workplace Study	Improving Workspaces Can Increase Productivity	3%	3%	3 x $812.50	$2,437.50	(General Services Administration, 2006)	$812.50 represents 1% of the average annual office worker salary nationwide. (See methods for more info)
Wyon	Improving Workspaces Can Increase Productivity	5% to 15%	10%	10 x $812.50	$8,125.00	(Wyon, 1996)	
Pollard	Improving Workspaces Can Increase Productivity	3% to 15%	9%	9 X $812.50	$7,312.50	(Clements-Croome, 2006)	
Roelofsen	Improving Workspaces Can Improve Worker Performance	5% to 15%	10%	10 x $812.50	$8,125.00	(Roelofsen, 2002)	
Lomonaco et al.	Physical Environment can Improve Worker Productivity	3% to 15%	9%	9 X $812.50	$7,312.50	(Lomonaco & Miller, 1997)	
CA Energy Commission	Characteristics of a worker's environment account for variation in worker productivity	2% to 5%	3.5%	3.5 X $812.50	$2,843.75	(CA Energy Commission, 2003)	
AT Kearney	A holistic approach to improving work environment leads to increased productivity	10%	10%	10 x $812.50	$8,125.00	(AT Kearney, 2015)	
Kroner et al.	Improving workplace conditions can lead to an increase in productivity	3%	3%	3 x $812.50	$2,437.50	(Kroner et al., 1992)	
Leyten	Good indoor environment increases productivity	10% to 15%	12.5%	12.5 X $812.50	$10,156.25	(Leyten & Boestra, 2003)	Indoor air was responsible for 3% to 7% of the increase
Lorsch	Physical environment may account for a variation in productivity	5% to 15%	10%	10 x $812.50	$8,125.00	(Lorsch, 1994)	
CBPD Analysis of 13 Studies	Good lighting, HVAC and access to windows can improve productivity between	3% to 18%	10.5%	10.5 X $812.50	$8,531.25	(Loftness & Hartkopf, 2003)	
Kats	Lighting and temperatures improvements lead to direct productivity gains of	.5% to 5%	2.8%	2.75 X $812.50	$2,234.38	(Kats, 2003)	
Fisk and Rosenfeld	Improving temperature and lighting can impact productivity between	.5% to 5%	2.75%	2.75 X $812.50	$2,234.38	(Fisk and Rosenfeld, 1997)	
	Average per person per year value of estimated productivity increases:				**$6,000.00**	**Workplace Impact on Productivity - Lab Studies and research estimates**	

Table 54. Source Data and References used for Quantitative and Qualitative Analyses – Post Occupancy Lighting Upgrades / Estimates of the Overall Impact of Light on Productivity

Study Name or Author	Research Findings	% Increase Per Employee Per Year	Value selected	Formula used	Converted to $/ employee/ year	Reference	Notes
Post Occupancy Field Studies that include lighting upgrades							
ASID HQ Post Occupancy Study	Productivity Increased in the New Building	16%	16%	16 x $812.50	$13,000.00	(Chung,2017)	
Lockheed renovation	Productivity Increased after Renovation	15%	15%	15 x $812.50	$12,187.50	(Edwards et al., 2002)	
West Bend Insurance	Productivity Increased in the New Building	12% - 14%	13%	13 x $812.50	$10,562.50	(Romm and Browning 1994)	
Niemela renovations	Productivity Increased after Renovation	9.1%	9.1%	9.1 x $812.50	$7,393.75	(Niemel et al., 2002)	
Conventional to LEED Study	Productivity increased at least	2.6%	2.6%	2.6 X $812.50	$2,112.50	(Singh et al., 2010)	
MacNaughton et al.	Workers in Certified Green Buildings Scored higher in tests of cognitive function compared to workers in non-certified, energy efficient buildings	26.4%	26.4%	26.4 X $406.25	$10,725.00	(MacNaughton et al., 2017)	
Study of 33 green buildings	Productivity increased and sick time was reduced in the new buildings	$36.90 to $55.30 per sq foot	$46.11/Sq ft	$46.11 psf X 151 sq ft/employee	$6,962.61	(Kats,2003)	
Survey of Energy Star and LEED	Productivity increased and sick time decreased in the LEED/Energy Star buildings	$6,200	$6,200	N/A	$6,200.00	(Miller, et al.,2009)	
	Average per person per year value of measured productivity increases:				**$8,642.98**	**Workplace Impact on Productivity - Field Studies**	

Studies of the impact of Lighting on Productivity - The Following Research Shows Productivity Increases Due to Improved Lighting Conditions

Study Name or Author	Research Findings	% Increase Per Employee Per Year	Value selected	Formula used	Converted to $/ employee/ year	Reference	Notes
Heschong et al.	Improved lighting increased worker productivity between	.7% to 23%	11.85%	11.85 X $812.50	$9,628.13	(Heschong et al., 2002)	
Kaczmarczyk and Morris	Improving lighting conditions increases worker productivity	12%	12%	12 X $812.50	$9,750.00	(Kaczmarczyk & Morris, 2002)	
Pennsylvania Power	Lighting upgrades led to productivity improvements	13%	13%	13 X $812.50	$10,562.50	(NIST, 1995)	
Post Office Renovation	Lighting retrofit led to productivity improvements	6%	6%	6 X $812.50	$4,875.00	(Romm, 1994)	
Abdou	Light can improve office worker performance	9%	9%	9 X $812.50	$7,312.50	(Abdou, 1997)	Also reports light can increase the productivity of factory workers by as much as 70%.
Stenzel Study	Increasing from 32 to 93 foot-candles increased average worker productivity	7.6%	7.6%	7.6 X $812.50	$6,175.00	(Stenzel 1962) (NEMA)	
Bommel et al.	Good lighting can increase productivity by	8.0%	8.0%	8 X $812.59	$6,500.00	(Bommel at al., 2002)	
NLB Lighting Renovation CA	Productivity increased after renovation	10.0%	10.0%	10 X $812.50	$8,125.00	(Abdou, 1997)	
NLB Lighting Renovation NY	Productivity increased after renovation	4.0%	4.0%	4 X $812.50	$3,250.00	(Abdou, 1997)	
CBPD	4 studies of direct/indirect lighting showed improved performance	3% to 23%	13%	13 X $812.50	$10,562.50	(Loftness & Hartkopf, 2003)	
CBPD	4 studies of quality fixtures, high performance ballasts and parabolic louvers	3% to 13.2%	8%	8.1 X $812.50	$6,581.25	(Loftness & Hartkopf, 2003)	
Heschong/Mahone Schools	Students with the most daylight progressed faster on math and reading tests	20% to 26%	23%	23 X $406.25	$9,343.75	(Heschong, 1999)	
	Avergage per person per year value of estimated productivity increases:				**$7,722.14**	**General Lighting Impact on Productivity**	

Table 55. Source Data and References used for Quantitative and Qualitative Analyses – Feature L01 Windows and Views

Research Pertaining to Specific WBSV2 Lighting Features and their Potential Impact on Productivity

L01 Light Exposure and Education

Quantitative Results

Study Name or Author	Research Findings	% Increase Per Employee Per Year	Value selected	Formula used	Converted to $/ employee/ year	Reference	Notes / Additional Benefits
Windows / Views							
Boubekri et al.	Workers with windows slept longer	46 minutes more sleep each night	46 Minutes	46 X $46.83	$2,154.18	(Boubekri, Cheung, Reid, Wang, & Zee, 2014)	See "methods" for $46.83 figure.
Lighting Research Center	Workers with a window worked apx 15% longer on work tasks than comparable workers in an interior space	$10,000/ occupant/ year	$10,000	$10,000	$10,000.00	(Figueiro, Rea, Rea, & Stevens, 2002)	Study also reported a 35% decrease in electric light use in windowed offices.
Heschong	Students with the largest windows had improved cognitive performance compared to student with the smallest windows on tests of math and reading.	15% to 23%	19.00%	19 X $406.25	$7,718.75	(Heschong, 1999)	Although the subjects in this study were students in a classroom environment, the magnitude of the learning improvements due to daylight exposure provides evidence that daylight has a strong impact on human cognitive performance and learning. Because the PNNL study below showed very similar results in office workers, this study was included here.
Sterling and Sterling 1983	Having access to windows increased productivity	3.20%	3.20%	3.2 X $812.50	$2,060.00	(Loftness & Hartkopf, 2003)	
DOE HQ	Having access to windows increased productivity	0.40%	0.40%	.4% X $812.50	$325.00	(Loftness & Hartkopf, 2003)	
CA Energy Commission	Better view associated with better worker performance. Processed calls faster	6-12%	9.00%	9 X $812.50	$7,312.50	(CA Energy Commission, 2003	
CA Energy Commission	Better view associated with better worker performance. Performed better on tests of cognitive performance.	10-25%	17.50%	17.5 X $406.25	$7,109.38	(CA Energy Commission, 2003	Office workers with better views also reported better health. Office workers with no views reported higher incidences of
PNNL, U Illinois 2011	Office workers seated within preferred zones with access to daylight and views scored Higher on tests of cognitive function	Up to 20% above average	20%	20 X $406.25	$8,125.00	(Edwards et al., 2002)	Cognitive test scores dropped as low as 24% below average for workers with no daylight or views.
	Average per person per year value of estimated productivity increases:				**$5,600.60**		

Table 56. Source Data and References used for Quantitative and Qualitative Analyses – Feature L01 Daylight / Circadian Lighting

Daylight / Circadian Lighting							
Verifone/Romm	Workers in daylit office increased individual productivity	5%	5%	5 X $812.50	$4,062.50	(Loftness & Hartkopf, 2003)	
Wilkins	Workers were more productive under daylight than fluorescent lighting	5%	5%	5 X $812.50	$4,062.50	(Wilkins, 1995)	
Heschong	Students with the most daylight had improved cognitive performance compared to students with the least amount of daylight. Students with the most daylight progressed faster on math and reading tests	20% to 26%	23%	23 X $406.25	$9,343.75	(Heschong, 1999)	Although the subjects in this study were students in a classroom environment, the magnitude of the learning improvements due to daylight exposure provides evidence that daylight has a strong impact on human cognitive performance and learning. Because the PNNL study below showed very similar results in office workers, this study was included here.
AT Kearny	Biologically appropriate lighting increases office worker productivity	1.15%	1.15%	1.15 X $812.50	$934.38	(AT Kearny, 2015)	
Al-Ashwal	Daylight successfully integrated with artificial light increased worker productivity	5% - 15%	10.00%	10 X $812.50	$8,125.00	(Al-Ashwal et al., 2018)	
Obayashi et al	Circadian lighting in the morning under 2,100 lux greatly improved productivity	10.00%	10.00%	10 X $812.50	$8,125.00	(Obayashi et al., 2007)	
Carnegie Melon	Daylight leads to improved productivity and reduced absenteeism	$226	$226	$226	$226.00	(Loftness et al., 2013)	This study based the $226 value off Figueiro's case study from 2002 (Below) and claimed daylight leads to a $3.75 % increase in productivity. However, in the original report Figueiro stated that daylight led to a 15% increase in time spent on task, which was worth $10,000 per employee per year based on a $70k salary in 2002. Therefore, this value seems to be an error and much lower than it should be. https://aceee.org/files/proceedings/2002/data/papers/SS02_Panel8_Paper06.pdf
Figueiro	Daylit office improved individual productivity	15%	15%	15 X $812.50	$12,187.50	(Figueiro, 2002)	The study's author reported the value of increased productivity as being $10,000. It has been adjusted to match current average salaries. (See methods)
Boubekri et al.	Workers with windows slept longer each night	46 minutes	46	46 X $46.83	$2,154.18	(Boubekri et al., 2014)	improvements.
PNNL, U Illinois 2011	Office workers w/ access to daylight and views scored higher on tests of cognitive function	Up to 20% above average	20%	20 X $406.25	$8,125.00	(Edwards et al., 2002)	Cognitive test scores dropped as low as 24% below average for workers with no daylight or views.
	Average per person per year value of estimated productivity increases:				**$5,734.58**		

Table 57. Source Data and References used for Quantitative and Qualitative Analyses – Absenteeism and Ancillary Benefits of Windows and Views

The Effect of Daylight and Views on Absenteeism								
ING Bank	After workers moved into a daylit building absenteeism dropped	15%	15%	.15 X $1,879.50	$281.93	(Edwards et al., 2002)	Absenteeism's cost to an employer is $1,879.50 per employee	
Lockheed Martin	After workers moved into a daylit building absenteeism dropped	15%	15%	.15 X $1,879.50	$281.93	(Romm & Browning 1994)		
VeriFone	After workers moved into a daylit building absenteeism dropped	6.8 hours	6.8 hours	6.8 x $39.06	$265.61	(Edwards et al., 2002)		
Benton	Daylight and dimming decreases absenteeism	15%	15.0%	.15 X $1,879.50	$281.93	(Loftness & Hartkopf, 2003)		
Thayer	Having access to daylight reduced absenteeism by	15%	15.0%	.15 X $1,879.50	$281.93	(Loftness et al., 2013)		
Rocky Mountain Institute	Daylit buildings reduce absenteeism	15%	15%	.15 X $1,879.50	$281.93	(Edwards et al., 2002)		
AT Kearney	Biologically appropriate light reduces sick days by 1%	1%	1%	.01 X $1,879.50	$18.80	AT Kearney, 2015)		
Elzeyadi	Having a view reduced sick days by 6.25% on average, up to 19.3%.	6.25% - 19.3%	12.78%	.1278 X $1,879.50	$240.20	(Elzeyadi, 2011)		
Elzeyadi	Workers w/ best quality lighting vs workers w/ worst used fewer sick days	16 hours	16 hours	16 X $39.06	$624.96	(Elzeyadi, 2011)	Going from worst conditions to best	
Elzeyadi	Workers w/ best quality lighting used fewer sick days than their average coworker	3.25%	3.25%	.0325 X $1,879.50	$61.08	(Elzeyadi, 2011)	This is the average	
Elzeyadi et al.	Windows, lighting quality and views reduced sick days	10%	10%	.10 X $1,879.50	$187.95	(Elzeyadi et al., 2017)		
	Average per person per year value of estimated productivity increases:				**$255.30**			
Qualitative/Subjective/Ancillary Benefits								
Study	**Measure**	**Financial**	**Well-Being**	**Health**	**Safety**	**Cognitive Function**	**Performance**	**Reference**
Windows / Views								
Large open office field study	Presence of window biggest indicator of satisfaction with lighting	X						(Veitch et al., 2003)
Kaplan	Workers with windows better cope with stress at work and home		X					(Clements-Croome, 2006)
Carnegie Mellon	Workers near windows had fewer health problems			X				(Edwards et al., 2002)
Yildirim et al.	Proximity to a window	X						(Yildirum et al., 2007)
Boubekri et al.	Workers with windows sleep better leading to	X	X	X X X X X	X	X X	XXXX	(Boubekri, Cheung, Reid, Wang, & Zee, 2014)
Kaplan	Workers with windowed offices		X X					(Clements-Croome, 2006)
Boyce, Et al.	Workers with Windows	X	X	X				(Boyce et al., 2003.)
Aries et al.	Workers with views	X	X	X X			X	(Aries et al, 2010)
CA Energy Commission	Workers with the best views			X XXX		X	X	(California Energy Commission, 2003)
Abdou	Students with windows	X	X	X			X	(Abdou, 1997)
Ruck 1989	Compared to windowless factories, factories w/ windows lead to			XXX			X	(Abdou, 1997
Elzeyadi	Views have an impact on						X	(Elzeyadi, 2011).
Boyce, et al.	Workers with Views					X		(Boyce et al., 2003.)
Elzeyadi	Windows have a significant impact on worker performance						X	(Elzeyadi, 2011).
		6	7	17	1	4	10	

Table 58. Source Data and References used for Quantitative and Qualitative Analyses – Ancillary Benefits of Daylight and Circadian Lighting

Qualitative/Subjective/Ancillary Benefits								
Study	**Measure**	**Financial**	**Well-Being**	**Health**	**Safety**	**Cognitive Function**	**Performance**	**Reference**
Daylight / Circadian Lighting								
Franta and Anstead	Workers in daylit office buildings reported	X		X X			X	(Franta and Anstead, 1994)
Boyce et al.	Daylight has a better chance of	X				X X	X X	(Boyce, Hunter, & Howlett, 2003)
Yildirim et al.	Sunlight has positive effect on worker subjective wellbeing. Employees prefer to work near windows and workplaces with natural lighting.	X	X					(Yildirim et al., 2007)
Elzeyadi	Workers in Daylit office buildings			X X X			XXX	(Elzeyadi, 2011)
CA Energy Commission	Higher levels of daylight					X X		(CA Energy Commission, 2003)
Rahman et al.	Daylight						X	(Rahman et al., 2014)
Figueiro et al.	Workers exposed to high levels of light as seen with daylight		X					(Figueiro et al., 2017)
Shishegar & Boubekri	Daylight has an impact on	X	XX	XX		X XX	XXXX	(Shishegar & Boubekri, 2016)
Edwards et al.	Workers in daylit office buildings	X						(Edwards et al., 2002)
Wilks et al.	Workers with more daylight			X				(Boyce et al., 2003.)
UK Health & Safety Executive	Daylight improves			X	X			(Great Britain Health and Safety Executive, 2002)
Rocky Mountain Institute	Daylit buildings had reduced employee turnover	X						(Edwards et al., 2002)
Figueiro, Nagare, & Price	Circadian lighting enables		X	XXXX		X	X	(Figueiro, Nagare, & Price, 2018)
Bommel et al.	Daylight has an impact on		X			X		(Bommel et al., 2002)
Boyce, et al.	Workers with Circadian Lighting		X	X			X	(Boyce et al., 2003)
Sahin et al.	Bright Light exposure during the day increases alertness						X	(Sahin, Wood, Plitnick, & Figueiro, 2014)
		6	7	14	1	9	14	

Table 59. Source Data and References used for Quantitative and Qualitative Analyses – Feature L02 Light Levels for Visual Acuity

L02 Visual Lighting Design

Quantitative Results

Study Name or Author	Research Findings	% Increase Per Employee Per Year	Value selected	Formula used	Converted to $/ employee/ year	Reference	Notes
Light levels for visual acuity							
Hughes and McNelis	Increasing from 500 to 1500 lx increased performance of office workers	9%	9%	9 X $812.50	$7,312.50	(Halonen et al., 2010)	
CA Energy Commission	Increasing from 80 to 100 footcandles led to an increase in cognitive performance	1%	1%	1 X 406.25	$406.25	(Heschong, 2003)	
Study of clerical workers	Increasing from 50 to 100 foot-candles increased productivity	5%	5%	5 X $812.50	$4,062.50	(Hughes, 1978)	
Study of clerical workers	Increasing from 50 to 150 foot-candles increased productivity	9%	9%	9 X $812.50	$7,312.50	(Hughes, 1978)	
Barnaby 1980	Increasing from 50 to 100 foot-candles increased productivity	0.7%	0.7%	.7 X $812.50	$568.75	(Loftness & Hartkopf, 2003)	
Barnaby 1980	Increasing from 50 to 150 foot-candles increased productivity	2%	2%	2 X $812.50	$1,625.00	(Loftness & Hartkopf, 2003)	
AT Kearney	Increasing light levels to 2000 lux in factories leads to a productivity increase	4.5%	4.5%	4.5 X $812.50	$3,656.25	(AT Kearney, 2015)	
Hedge, 2016	Increasing from 300 lux to 850 lux yields an increase in visual performance of	1%	1%	1 X $406.25	$406.25	(Hedge, 2016)	
Stenzel	Increasing from 350 lux to 1000 lux increased worker productivity by	7.6%	7.6%	7.6 X $812.50	$6,175.00	(Abdou, 1997)	
Julsen Literature Review	5 Studies show that increasing from between 250-400 lux to 1000 lux improved performance approximately 8%	8%	8%	8 X $812.50	$6,500.00	(Julsen & Tenner, 2005)	
Gifford Meta-analysis for illuminance	High illuminance of 1962 lux compared to very low 70 lux can improve office performance but difference may deteriorate after 15 minute adaptation period	0%	0%	0	$0.00	(Clements-Croome, 2006)	High illuminance vs very low may slightly improve worker performance - More light is not necessarily better as long as it is bright enough for seeing task details. Veitch
National Lighting Bureau	Raising light levels in poorly illuminated spaces can increase worker productivity	25%	25%	25 X $812.50	$20,312.50	(Abdou, 1997)	
National Lighting Bureau	Increasing light levels from 5 foot-candles to 50 foot-candles increased productivity	up to 13%	13%	13 X $812.50	$10,562.50	(Abdou, 1997)	
Obayashi et al.	Increasing from 700 lux to 2100 lux led to significantly higher productivity	> 9%	9%	9 X $812.50	$7,312.50	Obayashi et al., 2007)	
Juslen 2007	Increasing from 800 lux to 1200 lux increased worker productivity between	2.9% to 3.1%	3.00%	3 X $812.50	$2,437.50	(Juslen, 2007)	
Juslen, 2007	During night shift, going from 800 lux to 1200 lux increased worker productivity	7.7%	7.7%	7.7% X $812.50	$6,256.25	(Juslen, 2007)	
Juslen, 2007	Increasing illuminance increased productivity	5.5%	5.5%	5.5$ X $812.50	$4,468.75	(Juslen, 2007)	
Gligor	Literature shows more null results than clear cut effects of illuminance levels on tasks	0%	0%	0	$0.00	(Gligor, 2004)	
Bommel et al	Raising light levels from 100 lux to between 1000 and 4000 lux increases worker performance between	7% to 30%	18.5%	18.5% X 812.50	$15,031.25	(Bommel et al., 2002)	
Katzev	No significant cognitive performance benefits in 3 tests at different light levels	0%	0%	0	$0.00	(Katzev, 1992)	
MacNaughton et al., 2017	Brighter lighting in the workplace led to higher sleep scores. 211 lx brighter buildings had 6.4% higher sleep scores equating to .72% increase in cognitive function.	0.72%	0.72%	.72 X $812.50	$585.00	(MacNaughton et al., 2017)	
	Avergage per person per year value of estimated productivity increases:				**$4,999.58**		

Table 60. Source Data and References used for Quantitative and Qualitative Analyses – Feature L02 Ancillary Benefits

Qualitative/Subjective/Ancillary Benefits								
Study	**Measure**	**Financial**	**Well-Being**	**Health**	**Safety**	**Cognitive Function**	**Performance**	**Reference**
Light Levels for Visual Acuity (based on activity and age)								
Carli, Giuli, & Zecchin	Higher lighting levels increase performance						X X	(Carli, Giuli, & Zecchin, 2008)
Parsons 2000, Nave 1984	Good lighting levels increase performance			X X			X	(Parsons, 2000, Nave 1984).
Smolders 2012	Higher luminance leads to	X				X	X X X	(Smolders, de Kort, & Cluitmans, 2012)
Weston	Providing adequate illuminance for visual tasks increases productivity						X	(Weston, 1922)
Weston	Providing adequate illuminance for visual tasks increases productivity						X	(Weston, 1922)
Baron, Rea & Daniels	Illuminance has a significant impact on	X	XX			X	X X	(Baron et al, 1992)
Allen , 1982	Increased illuminance increases productivity						X	(Katzev, 1992)
Gaetjens 1942	Increased illuminance increases productivity						X	(Katzev, 1992)
Irens, 1960	Increased illuminance increases productivity						X	(Katzev, 1992)
Swale, 1943	Increased illuminance increases productivity						X	(Katzev, 1992)
Stenzel, 1962	Increased illuminance increases productivity						X	(Katzev, 1992)
Phipps-Nelson et al.	Bright light (1000 lux) vs dim light (5 lux) leads to		X			X	X	(Katzev, 1992)
Abdou	Raising illuminance above 500 lux leads to improved performance						X	(Abdou, 1997)
Aries, 2005	High levels of illuminance (>100 lux) decrease fatigue and increase alertness						XX	(Aries, 2005)
Sucov	Increasing illumination from 15 to 100 foot-candles decreased accidents by 50%				X			(Abdou, 1997)
Shieh & Lin	Visual performance under 450 lux is greatly improved compared to 200 lux						X	(Shieh & Lin, 2000)
Bommel et al.	Raising illuminance from 300 lux to 2000 lux reduced accidents by 52%				XX			(Bommel et al, 2002)
Chung & Lu	250 lux causes greater eye fatigue than 500 lux			X			X	(Chung & Lu, 2003)
Juslen 2007	Light brighter than minimum recommendations leads to	X				XX	XXX	(Juslen, 2007)
Zakerian et al	Increasing the intensity of light leads to			XXX	X		X	(Zakerian et al, 2018)
UK Health and Safety Executive	Increasing previously insufficient light on the task			X	X			(Great Britain & Health and
		3	3	7	5	5	25	

Table 61. Source Data and References used for Quantitative and Qualitative Analyses – Feature L03 Circadian Lighting / L04 Solar Glare

L03 Circadian Lighting Design

The benefits of Circadian Lighting have been covered under Feature L01. The main difference between L01 and L03 in terms of circadian lighting is for L01 daylight (circadian lighting) must be achieved in 30% of occupied spaces, while for L03 circadian lighting (daylight or artificial) must be achieved in all regularly occupied spaces.

L04 Glare Control

Quantitative Results

Study Name or Author	Research Findings	% Increase Per Employee Per Year	Value selected	Formula used	Converted to $/ employee/ year	Reference	Notes
Solar Glare Through Windows							
Heschong Study 1 Call Center	Glare decreased worker performance between	15% to 21%	18%	18% X $406.25 = $7,312.50 X 12.5% of work year = $914.06/ employee/ year X 4% = $914.06/ employee affected by glare	$36.56	(CA Energy Commission, 2003).	This only impacts employees during glare situations. Not all workstations are impacted. For the model office space ASE 1000/250 was exceeded in 4% of building. This model will assume 4% of workers were exposed to glare for 250 hours per year. That number will be factored across all emplyees to come up with a per employee per year value. $406.25 = 1/2 1% of annual salary of an average worker.
Wymelenberg	Occupants in preferred lighting perform better than those in uncomfortable glare	12.3%	12.3%	See above but change 18% to 12.3%	$24.98	(Wymelenberg, 2013)	
Zhang and Alton	Controlling glare can increase productivity and decrease absenteeism and is worth	$187	$187	$187	$187.00	(Zhang & Alton, 2010)	
				Average per person per year value of estimated productivity increases:	**$82.85**		

Table 62. Source Data and References used for Quantitative and Qualitative Analyses – Feature L04 Solar Glare Quantitative and Ancillary Benefits

Quantitative Results

Study Name or Author	Research Findings	% Increase Per Employee Per Year	Value selected	Formula used	Converted to $/ employee/ year	Reference	Notes
Glare from Light Fixtures							
Hedge et al - 1995	Lensed Indirect lighting vs parabolic louver increased productivity	3%	3%	3 X $812.50	$2,437.50	(Loftness & Hartkopf, 2003)	
Allen	Lighting change designed to reduce veiling glare from fixtures lead to an increase in productivity despite dropping illuminance from 1450-1610 lux to 1070 -1400 lux.	13.2%	13.2%	13.2 X $812.50	$10,725.00	(Abdou, 1997)	
Reno Post Office	Indirect lighting upgrade reduced glare and increased productivity	6%	6%	6 X $812.50	$4,875.00	(Loftness & Hartkopf, 2003)	
1992 IEEE Industry Applications Society Annual Meeting	Under high levels of discomfort due to glare there was a decrease in visual task efficiency	3%	3%	3 X $406.25	$1,218.75	(CA Energy Commission, 2003).	
	Average per person per year value of estimated productivity increases:				**$4,814.06**		

Qualitative/Subjective/Ancillary Benefits

Study	Measure	Financial	Well-Being	Health	Safety	Cognitive Function	Performance	Reference
Solar Disability, discomfort and veiling glare								
Linney	Reducing solar glare through windows leads to	X	XXX	XX		XX	XXXXX	(Linney, 2008)
Brotas and Wienold	Reducing uncontrolled glare leads to	X			X		X	(Brotas & Wirnold, 2014)
Bommel et al.	Reducing glare decreases accidents				X			(Bommel et al., 2002)
Zhang & Alton	Controlling solar glare leads to less discomfort and fatigue		X				X	(Zhang & Alton, 2010)
		2	4	2	2	2	7	

Qualitative/Subjective/Ancillary Benefits

Study	Measure	Financial	Well-Being	Health	Safety	Cognitive Function	Performance	Reference
Disability, Discomfort and veiling glare from Artificial Light								
Abdou	Reducing glare from artificial lighting improves	X	X				X	(Abdou, 1997)
Sundstrom	Reducing glare from artificial lighting improves	X					X	(Sundstrom and Sundstrom, 1986)
Bommel et al.	Reducing glare decreases accidents				X			(Bommel et al., 2002)
		2	1	0	1	0	2	

Table 63. Source Data and References used for Quantitative and Qualitative Analyses – Feature L05 Enhanced Daylight / L06 Visual Balance

L05 Enhanced Daylight Access

The benefits of daylight have been covered under Feature L01. With this Feature it is increasing the number of workers who are impacted by circadian lighting.

L06 Visual Balance

Quantitative Results

Study Name or Author	Research Findings	% Increase Per Employee Per Year	Value selected	Formula used	Converted to $/ employee/ year	Reference	Notes
Illuminance Balance							
Cushman et al.	Luminance ratios far in excess of ratios listed in WBSv2 had minimal effect on performance	0	0	0	0	(Cushman et al., 1984)	
Parpairi et al.	Luminance ratios far from the recommended 3:1 and 10:1 ratios were still rated as comfortable and satisfactory by users in real world offices	0	0	0	0	(Parpairi et al, 2002)	
Linney	Luminance ratios ten times higher than those in the WBSv2 were still considered comfortable	0	0	0	0	(Linney, 2008)	
Osterhaus	Office workers can be comfortable and productive under 1000:1 luminance rations (100 times higher than those in the WBSv2) if a desirable view of the outdoor environment is available.	0	0	0	0	(Osterhaus, 2002)	
	Average per person per year value of estimated productivity increases:				**$0.00**		

Quantitative Results

Study Name or Author	Research Findings	% Increase Per Employee Per Year	Value selected	Formula used	Converted to $/ employee/ year	Reference	Notes
Dimming Speed							
Juslen 2007	Changing the dimming speed did not affect productivity	0	0	0	$0.00	(Juslen, 2007)	
Newsham et al	By slowing the dimming rate to 10 lux/minute a 50% drop in illumination is undetected. There is no strong evidence that moderate lighting ramps will affect productivity positively or negatively as long as the final illumination is not low enough to impact productivity.	0	0	0	$0.00	(Newsham et al., 2007)	
		0	0	0	$0.00		

Table 64. Source Data and References used for Quantitative and Qualitative Analyses – Feature L06 Ancillary Benefits / L07 Electric Light Quality

Qualitative/Subjective/Ancillary Benefits

Study	Measure	Financial	Well-Being	Health	Safety	Cognitive Function	Performance	Reference
Illuminance Balance								
UK Health and Safety Executive	Uneven Lighting can lead to				X			(Great Britain & Health and Safety Executive, 2002)
Wibom & Carlsson 1987	Reducing excessive luminance ratios can lead to			XX			X	(Carli et al., 2008)
De Vries et al	Increasing wall luminance leads to						X	(de Vries, Souman et al., 2018)
Carli et al.	Providing a proper luminance ratio (desk/paper) leads to	X						(Carli et al., 2008)
Cushman et al.	Reducing excessive luminance ratios can decreases errors but also decreases productivity					X		(Cushman, 1984)
		1	0	2	1	0	2	

L07 Electric Light Quality

Quantitative Results

Study Name or Author	Research Findings	% Increase Per Employee Per Year	Value selected	Formula used	Converted to $/ employee/ year	Reference	Notes
Color Rendering/Full Spectrum Lighting							
Hedge	For tasks such as reading, the spectral power distribution plays a very minor role. For tasks that requires discrimination of subtle shades of hue or lightness, spectral power distribution plays an essential role.	**0**	**0**	**0**	**0**	(Hedge, 2016)	
Fisk and Rosenfeld	No strong or consistent scientific evidence of benefits of full spectrum light according to Boray et al., 2989;Veitch at al., 1991; NEMA, 1989	**0**	**0**	**0**	**0**	(Fisk and Rosenfeld, 1997)	
Veitch	Several laboratory studies failed to find effects of lamp spectra composition on visual performance or visual acuity	**0**	**0**	**0**	**0**	(Veitch et al, 1995)	
Carli et al	Full spectrum lighting did not show significant effects on worker performance, fatigue or visibility	**0**	**0**	**0**	**0**	(Carli et al., 2008)	
Veitch 1997	No difference between cool white and high CRI Full Spectrum lamps in measures of performance or mood.	**0**	**0**	**0**	**0**	(Veitch, 1997)	
Veitch 2001	No evidence that CRI has productivity benefits. CRI might induce positive affect but no test of this hypothesis exists.	**0**	**0**	**0**	**0**	(Veitch, 2001)	
	Average per person per year value of estimated productivity increases:				**$0.00**		

Table 65. Source Data and References used for Quantitative and Qualitative Analyses – L07 Managing Flicker

Quantitative Results							
Study Name or Author	**Research Findings**	**% Increase Per Employee Per Year**	**Value selected**	**Formula used**	**Converted to $/ employee/ year**	**Reference**	**Notes**
Managing Flicker							
Kuller and Laike 1998	High frequency elecronic ballast w/ reduced flicker led to productivity increase	3.20%	3.20%	3.2 X $812.50	$2,600.00	(Loftness & Hartkopf, 2003)	
Bommel et al.	Reducing low frequency flicker improves productivity between	.2% to 1%	0.60%	.6 X $812.50	$487.50	(Bommel et al., 2002)	
Fleming	Neither flicker frequency nor modulation depth affect health symptoms or productivity.	0.00%	0.00%	0	$0.00	(Fleming, 2003)	
Nelson et al.	Flicker frequency had no effect on performance on a number of different tasks	0.00%	0.00%	0	$0.00	Nelson, et al., 1996	
	Avergage per person per year value of estimated productivity increases:				**$771.88**		

Table 66. Source Data and References used for Quantitative and Qualitative Analyses – L07 Ancillary Benefits

Qualitative/Subjective/Ancillary Benefits

Study	Measure	Financial	Well-Being	Health	Safety	Cognitive Function	Performance	Reference
Color Rendering/Full spectrum lighting								
Boyce, 2003	A high CRI improves productivity when working with fine color discrimination						X	(Boyce, 2003)
Nickerson, 1960	A high CRI leads to						X	(Nickerson, 1960)
ASTM, 1996	A high CRI leads to						X	(ASTM, 1996)
Blackwell	Full spectrum light improved acuity and reduced fatigue						XX	(Blackwell, 1985)
Maas et al	Full spectrum light improved acuity and reduced fatigue						XX	(Mass et al, 1974)
Abdou	Artificial daylight reduced errors compared to high pressure sodium					X		(Abdou, 1997)
Bommel et al.	Improving color rendering can improve safety				X			(Bommel et al., 2002)
Knez 2001	CRI and/or Color of light has a significant impact on		X			X	X	(Knez, 2001)
Boyce	A Hight CRI is important for work involving fine color discrimination						X	(Boyce, 2003)
		0	1	0	1	2	0	

Qualitative/Subjective/Ancillary Benefits

Study	Measure	Financial	Well-Being	Health	Safety	Cognitive Function	Performance	Reference
Managing Flicker								
UK Health and Safety Executive	Managing low frequency flicker in lighting systems may lead to			X	X			(Great Britain & Health and Safety Executive, 2002)
Veitch & Newsham	Eliminating low frequency ballast flicker led to						X	(Veitch & Newsham, 1998)
Wilkins et al.	Eliminating low frequency ballast flicker leads to		X	X X				(Clements-Croome, 2006)
Lindner and Kropf	Eliminating low frequency ballast flicker			X X X				(Lindner and Kropf, 1993)
Boyce et al.	Reducing flicker improves		X	X			X	(Boyce et al., 2003)
Rey and Rey	Low frequency flicker increases error rate					X		(Rey & Rey, 1965)
Veitch et al.	Eliminating low frequency flicker leads to			XX			X	(Veitch, 2006)
Bullough et al.	Low frequency flicker slightly reduces comfort	X						(Bullough et al., 2011)
Bommel et al.	Low frequency flicker leads to stress and stress and headaches		XXX	X			X	(Bommel et al., 2002)
		1	4	10	1	1	4	

Table 67. Source Data and References used for Quantitative and Qualitative Analyses – Feature L08 Tunable CCT and Light Color

L08 Occupant Control of Lighting

Quantitative Results

Study Name or Author	Research Findings	% Increase Per Employee Per Year	Value selected	Formula used	Converted to $/ employee/ year	Reference	Notes
Tunable Lighting, Corelated Color Temperature and Light Color							
Knez	Cognitive performance scores were 20% higher under 3,000k vs 5,500	10% - 20%	15	15 X $406.25	$6,093.75	(Knez, 2001)	
Mills et al.	Worker performance improved with the use of very high CCT (17,000k) fixtures	19.40%	19.4	19.4 X $812.50	$15,762.50	(Mills, 2007)	
Ishii et al.	Cognitive performance increased with 6,200K task light when compared to 5,000K	5%	5%	5 X $406.25	$2,031.25	(Ishii et al., 2018)	
Juslen	Raising illuminance from 3,500K to 4,400K increased worker productivity by 5.7%	5.70%	5.70%	5.7%X 812.50	$4,631.25	(Juslen, 2007)	
Veitch & McColl	Lamp type (including full spectrum) does not appear to be the important factor in relation to visual performance or comfort.	0	0	0	0	(Veitch & McColl, 1995)	
Boray et al.	There were no significant differences between warm, cool or full spectrum lamps on 9 measure of performance and behavior	0	0	0	0	(Boray et al., 1989)	
Sivaji et al.	No significant difference in performance between warm while, cool white and day light	0	0	0	0	(Sivaji et al, 2013)	
Shamsul et al.	Typists performed better under cool white light compared to warm white light	7	7	6.7 X $812.50	5,443.75	(Shamsul et al, 2013)	
Knez & Kers 2000	Color of light has no significant impact on cognitive performance	0	0	0	0	(Knez & Kers, 2000)	
Knez & Enmarker 1998	Color of light has no impact on cognitive performance	0	0	0	0	(Knez & Enmarker, 1998)	
	Average per person per year value of estimated productivity increases:				**$4,245.31**		

Quantitative Results

Study Name or Author	Research Findings	% Increase Per Employee Per Year	Value selected	Formula used	Converted to $/ employee/ year	Reference	Notes
Light Color							
Knez & Kers 2000	Color of light has no significant impact on cognitive performance	0	0	0	0	(Knez & Kers, 2000)	
Knez & Enmarker 1998	Color of light has no impact on cognitive performance	0	0	0	0	(Knez & Enmarker, 1998)	
					$0.00		

Table 68. Source Data and References used for Quantitative and Qualitative Analyses – Feature L08 Personal Control

Quantitative Results

Study Name or Author	Research Findings	% Increase Per Employee Per Year	Value selected	Formula used	Converted to $/ employee/ year	Reference	Notes
Personal Control / Lighting Controls / Task lights							
Juslen	Having controllable task lighting increased productivity	4.50%	4.50%	4 X $812.50	$3,656.25	(Juslen et al., 2007)	
Veitch & Newsham	Having controls did not lead to improved health, mood, satisfaction or performance.	0.00%	0.00%	0	$0.00	(Veitch & Newsham, 2000)	
Study of clerical workers	Compared to a 50 foot-candle baseline, being able to raise illumination level as high as 150 footcandles increases productivity	5% to 9%	7%	7 X $812.50	$5,687.50	(Hughes, 1978)	
Barnaby	Compared to a 50 foot-candle baseline, being able to raise illumination level as high as 150 foo-tcandles increases productivity	.7% to 2%	1%	1.35% X $812.50	$1,096.88	(Loftness & Hartkopf, 2003)	
Lovins	Personal controls (including lighting and HVAC) increased productivity	2.80%	2.80%	2.8 X $812.50	$2,275.00	(Edwards et al., 2002)	
Kats	Lighting controls provide measured benefits in workforce productivity gains	7.1%	7.1%	7.1 X $812.50	$5,768.75	(Kats, 2003)	Report specifically mentions daylight provides significant improvements beyond the 7.1% listed here for lighting controls
Nishihara	When subjects could control their own task lights researchers noted an 11% improvement in cognitive performance.	11%	11%	11 X 406.25	4,468.75	(Loftness et al, 2013)	
	Average per person per year value of estimated productivity increases:				**$3,279.02**		

Table 69. Source Data and References used for Quantitative and Qualitative Analyses – Feature L08 Ancillary Benefits of Tunable Lighting

Qualitative/Subjective/Ancillary Benefits								
Study	**Measure**	**Financial**	**Well-Being**	**Health**	**Safety**	**Cognitive Function**	**Performance**	**Reference**
Tunable Lighting/ Correlated Color Temperature / Light Color								
Mills et al.	High CCT fixtures led to	X		X			XXX	(Mills et al., 2007)
Askipoor et al.	Different wavelengths of light have different affects throughout the day.					X	XXX	(Askipoor et al. 2018)
Juslen	Lighting CCT has a significant impact on mood		X				X	(Juslen et al., 2007)
McCloughan et al.	Lighting CCT Impacts mood		X				X	(McCloughan et al, 1999)
Knez	CCT impacts mood differently between older and younger subjects	X	X				X	(Knez, 2001)
Knez	Participants overall performed better under 3,000K CCT than 4,000 or 5,500					XXX	XXX	(Knez, 2001)
Askipoor et al.	Red light and Blue Light		XX	X	X	XX	XXXX	(Askipoor et al. 2018)
Wei et al.	CCT has a strong impact on	XX	XX				XX	(Wei et al., 2014)
Baron et al.	Lamp color has a significant effect on	X	XX			X	XX	(Baron et al. 1992)
Deguchi and Sato	Compared to 3000k light, 7,500k light leads to					X	XX	(Burattini, 2019)
Viola	Compared to 4,000k light, 17,000k light leads to		X			X	XX	(Mills et al., 2007)
Shamsul et al.	Alertness improved, performance increased and fewer errors occurred under 6,500 K light. Typing speed improved under 3,000 K.					XX	XX	(Shamsul et al., 2013)
Ferlazzo et al.	Cool white light leads to enhanced cognitive performance.					XXX	X	(Ferlazzo et al., 2014)
Mills	Compared to 4,000k light, 17,000k light leads to		XX			X	XX	(Mills et al., 2007)
Chellappa et al	Compared to 2500K and 3000k light sources, 6500K lights led to significant improvements in		X			X	XXXX	(Chellappa et al. 2011)
Figueiro	Red and blue light has an alerting effect					X	X	(Figueiro, 2018)
Chung and Pease	Yellow light causes pupil size to increase which may lead to increased eye fatigue and reduced visual performance			X			X	(Chung & Lu, 2003)
Lin and Huang	White light is better than yellow because yellow increases eye fatigue and reduced visual performance			X			X	(Lin & Huang, 2014)
Kaplan and Kaplan	Red light in the evening can improve mental health		X	X				(Kaplan & Kaplan,
		5	14	4	1	17	36	

Table 70. Source Data and References used for Quantitative and Qualitative Analyses – Feature L08 Ancillary Benefits of Personal Lighting Controls

Qualitative/Subjective/Ancillary Benefits								
Study	**Measure**	**Financial**	**Well-Being**	**Health**	**Safety**	**Cognitive Function**	**Performance**	**Reference**
Personal Control / Lighting Controls / Task Lights								
DYG Inc Study for Knoll	Workers who were happy with their lighting	X X						(DYG, Inc., 1998)
Bergs	The less the interior climate is centrally controlled	XX		X			X	(Bergs, 2002)
Juslén & Tenner	Giving workers the ability to select their preferred lighting levels leads to	X						(Juslén & Tenner, 2005)
Küller et al.	Workers moods were highest when light was at their preferred level		XX					(Küller, Ballal, Laike, Mikellides, & Tonello, 2006)
Newson and Veitch	The closer the lighting is to a workers preferred level the better their mood	X	X					(Veitch & Newsom, 2000)
Leaman and Bordass	Individual control of the environment leads to						X	(Leaman & Bordass, 1999)
Boyce et al.	individual control increases motivation and vigilance over the day					XX		(Carli et al., 2008)
Hoffmann et al	Adjusting lights throughout the day improved		X				XXX	(Küller, Ballal, Laike, Mikellides, & Tonello, 2006)
Barnes	Personal lighting controls improve	XX					X	(Clements-Croome, 2006)
Veitch & Newsom	81% of subjects were more satisfied when able to adjust lighting	X						(Veitch & Newsham, 2000)
Simpson	Personal lighting controls improve	XX					X	(Clements-Croome, 2006)
Cakir and Cakir	Workers with separate task and ambient lighting had 19% fewer headaches			X				(Loftness et al, 2013)
		11	4	2	0	2	7	

Appendix 2

MOS Luminaires Deficient for Feature L07

Table 71. Fixture type and count of luminaires installed in MOS that did not meet CRI minimum for Feature L07.

Project fixture type	Manufacturer and Model	CRI	Is fixture available with higher CRI?	Number of Fixtures
LA-N 2’	Amerlux Linea Linear LED fixture	83	Yes - 92	45
LB	Ecosense Linera 04LC-X-30-X-120	80	No	13
LC	Ecosense Linera 04LC-X-30-X-120	80	No	4
LE	Gruv FL Grid GB-5-LED	>80	No	1
LG	Phillips BR LED E26 BR	80	No	45
LJ	Gruv FL Grid GB-5-LED	>80	No	12
LN	Gruv FL Grid GB-5-LED	>80	No	4
LH	Gruv FL Grid GB-5-LED	>80	No	10
LP	Hornet RTLX-2 2-12-LED-E	85	Yes - 90+	19
LQ	Flos LED 03.2630.XX	85	No	6
RA	Evoke Generation 2 E4 75sd-g2	85	No	13
RA-A	Evoke Generation 2 E4 75sd-g2	85	No	12
RA-B	Evoke Generation 2 E4 75sd-g2	85	No	0
RC	Evoke Generation 2 E4 75sd-g2	85	No	11
RD	Evoke Generation 2 E4 75sd-g2	85	No	4
RE	Evoke Generation 2 E4 75sd-g2	85	No	22
RE-A	Evoke Generation 2 E4 75sd-g2	85	No	20
RF	Evoke Generation 2 E4 75sd-g2	85	No	50
RF-A	Evoke Generation 2 E4 75sd-g2	85	No	30
RG	Evoke Generation 2 E4 75sd-g2	85	No	102
TA	Hornet Track Head 15-LED-E	85	Yes - 90+	5
TB	Hornet Track Head 15-LED-E	85	Yes - 90+	1
TC-A	Cylindrix vertical CYLTV MR16	83	Yes - 97+	19
TC-B	Cylindrix vertical CYLTV MR16	83	Yes - 97+	21
TC-C	Cylindrix vertical CYLTV MR16	83	Yes - 97+	7
TD	HORNET-15-LED-E-BT-TN1	85	Yes - 90+	18
		Fixture	Total	494

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Ancillary Appendix

Supporting Lighting Control Manufacturer Documentation

Cut sheet showing that electronic ballasts installed at MOS operate at frequencies higher than required by Feature L07.

Fluorescent Dimming Ballasts **EcoSystem® H-Series** **Architectural Dimming**

369268 2 08.27.12

Specifications

Regulatory Approvals

- California Energy Commission Listed.
- UL Listed (evaluated to the requirements of UL935).
- CSA certified (evaluated to the requirements of C22.2 No. 74).
- Class P thermally protected.
- Meets ANSI C82.11 High Frequency Ballast Standard.
- Meets FCC Part 18 Non-Consumer requirements for EMI/RFI emissions.
- Meets ANSI C62.41 Category A surge protection standards up to and including 4 kV.
- Manufacturing facilities employ ESD reduction practices that comply with the requirements of ANSI/ESD S20.20.
- Lutron® Quality Systems registered to ISO9001.2008.

Ballast Wiring & Mounting

- Ballast is grounded via a mounting screw to the fixture.
- Ballast mounts using two screws (or sheet metal feature and one screw) within a fluorescent fixture.
- Power and lamp wiring terminals accept one 18 to 16 AWG (0.75 to 1.5 mm²) solid copper wire per terminal.

Lamp Seasoning

Refer to the lamp manufacturer's requirements for lamp seasoning requirements prior to dimming.

Performance

- Dimming Range: 100% to 0.7% measured Relative Light Output (RLO) for T8, 100% to 1% RLO for T5 and T5HO.
- Lamp Starting: programmed rapid start
- Lamp Current Crest Factor: less than 1.7
- Lamp Flicker: none visible
- Light Output Variation: constant ±2% light output for line voltage variations of ±10%
- Lamp Life: average lamp life meets or exceeds rating of lamp manufacturer.
- Power Factor: greater than 0.95
- Typical Total Harmonic Distortion (THD) less than 10% *
- Operating Voltage: Universal input 120 V~, 220/240 V~, 277 V~ at 50 or 60 Hz
- Frequency of Operation: greater than 42 kHz
- Ballast Factor (BF): 1.0/1.17 for T8 lamps and 1.0 for T5 and T5HO lamps
- Standby Power: less than 1 W

Dimming Range for T8 lamps:

BF	Dimming Range (Max/Min [BF])	Dimming Ratio
1.17	1.17 / 0.0085	138:1
1.0	1.00 / 0.0085	118:1

Dimming Range for T5 and T5HO lamps:

BF	Dimming Range (Max/Min [BF])	Dimming Ratio
1.0	1.00 / 0.01	100:1

Cut sheet showing drivers installed at MOS operate at 240 Hz.

Hi-lume 1% EcoSystem LED Driver with Soft-on, Fade-to-Black

Hi-lume 1% EcoSystem LED Drivers with Soft-on, Fade-to-Black provide a high-performance solution for any space, in any application. They provide smooth, continuous dimming down to 1% of full output current, and fade smoothly between 0% and 1% with Soft-on, Fade-to-Black.

Features

- UL® Listed Class P.
- UL® Type TL rated. Visit "Online Certificates Directory" at www.ul.com, enter file number "E322469" to determine the Type TL numbers specific to the LDEx model Lutron LED Driver.
- Soft-on, Fade-to-Black: fades smoothly between 0% and 1% when turned on and off for an incandescent-like experience.
- Continuous, flicker-free dimming from 100% to 1%[1].
- Dimming Method:
  - Constant-current reduction dimming provides video-friendly performance down to 5%
  - PWM dimming below 5% (240 Hz), % Modulation = 100%
- Guaranteed dimming performance when used with Lutron EcoSystem controls.
- Guaranteed compatibility with Energi Savr Node units with EcoSystem, GRAFIK Eye QS with EcoSystem, PowPak dimming module with EcoSystem, and Quantum systems, allowing for integration into a planned or existing EcoSystem lighting control solution.
- QwikFig compatible models available, see **How to Build a Model Number** page for details. For more information, please refer to the QwikFig User Guide (Lutron P/N 041473) or contact your Lutron sales representative.
- Protected from miswires of input power to EcoSystem control inputs up to 277 V~.
- Rated lifetime of 50,000 hours at 75 °C (167 °F) calibration point (t_c).
- FCC Part 15 Class A
- 100% performance tested at factory before shipping.
- RoHS compliant.

Case type K
3.00 in (76 mm) W × 1.00 in (25 mm) H × 4.90 in (124 mm) L

Case type M
1.18 in (30 mm) W × 1.00 in (25 mm) H × 14.13 in (359 mm) L

- Non-volatile memory restores all settings after power failure.
- For more information please visit: www.lutron.com/hilume1softbled

EcoSystem Features

- Simpler to wire and more reliable than 0–10 V⎓.
- Guarantees compatibility between Lutron controls, LED drivers, ballasts, and sensors.
- Accommodates zone and control changes without rewiring.
- Link to Lutron Quantum Total Light Management System to monitor lighting power consumption.
- Polarity-free and topology-free.
- Digital EcoSystem intelligence allows easy code compliance.
- Digital EcoSystem control link can be Class 1 or Class 2.

[1] Light output at 1% depends on the efficacy of the LED light engine used with the driver.

Quote to upgrade existing lighting control system to meet requirements of Feature L08.

LUTRON®

To: Shaun Taylor – Lutron Electronics Co., Inc.

From: Jeremy McCavera – Lutron Electronics Co., Inc.

Date: 7/15/2019

Re.: Project G – Washington DC
Network Lighting Control Upgrade

Cc: Ken Kiernan - Lutron Electronics Co., Inc.

Per your request, Lutron Electronics Co. (Lutron) is pleased to provide the following Proposal Letter for the Network Lighting Control upgrade for the above referenced project. Lutron Electronics Co. Inc. has completed a full estimating take-off and has made design decisions based on our sole interpretation of the project stated herein and are hereby submitting a LOT Price BUDGET Proposal in lieu of a detailed bill of material.

For the existing "model office space" based on drawings and the ability to integrate to the existing Lutron System, we would propose a BUDGET of $3,000.00 (Inclusive of ED and EC Mark-up) in order to support current design criteria.

- Design criteria inclusive of the control of proposed color changing/tunable white, lighting fixtures. (Light Fixture Pricing NOT included in this proposal)
- Additional wireless lighting controls to allow adjustment for both light intensity, and color adjustment.
- Upon completion of the installation the Lutron Service Co. will be deployed to the site to provide database merge, control programming, end user training and official turnover to the client.

Please feel free contact me with any questions or comments regarding this project and thank you for your interest in our specialized services

Sincerely,

Jeremy C. McCavera
Director, Commercial Projects
Lutron Electronics Co., Inc.